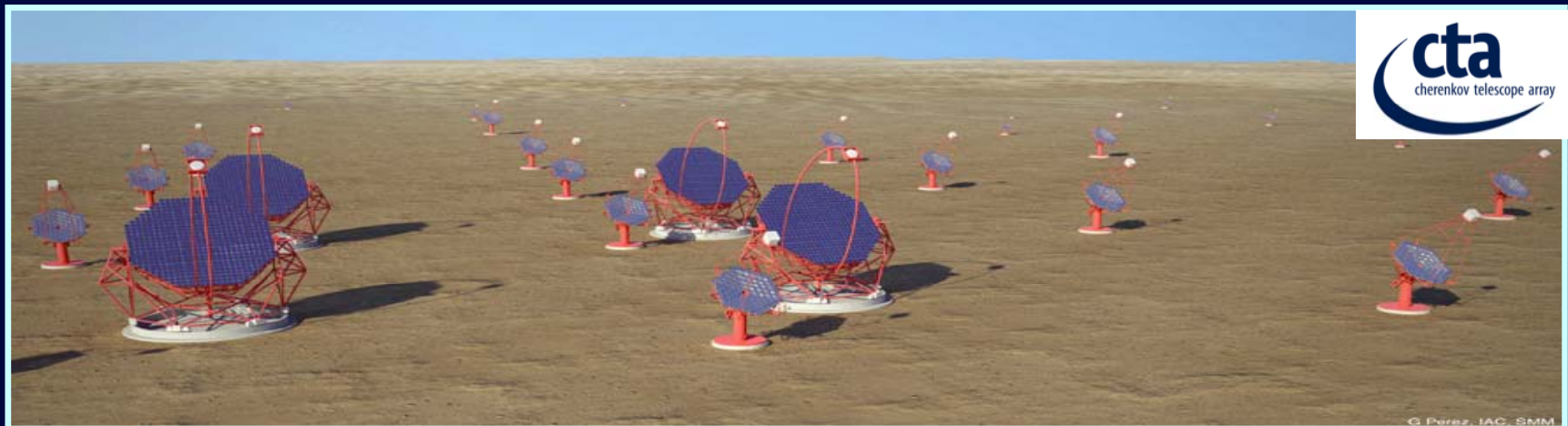


# Very High-Energy Astrophysics & The Cherenkov Telescope Array

Rene A. Ong (UCLA)

**SESE Colloquium, ASU, 6 Sept 2017**



- **Scientific & Technical Motivation**

Gamma rays – high energy light → a new astronomy

Three selected science topics in brief

Experimental Technique

Planning for the Future → CTA

- **Cherenkov Telescope Array (CTA)**

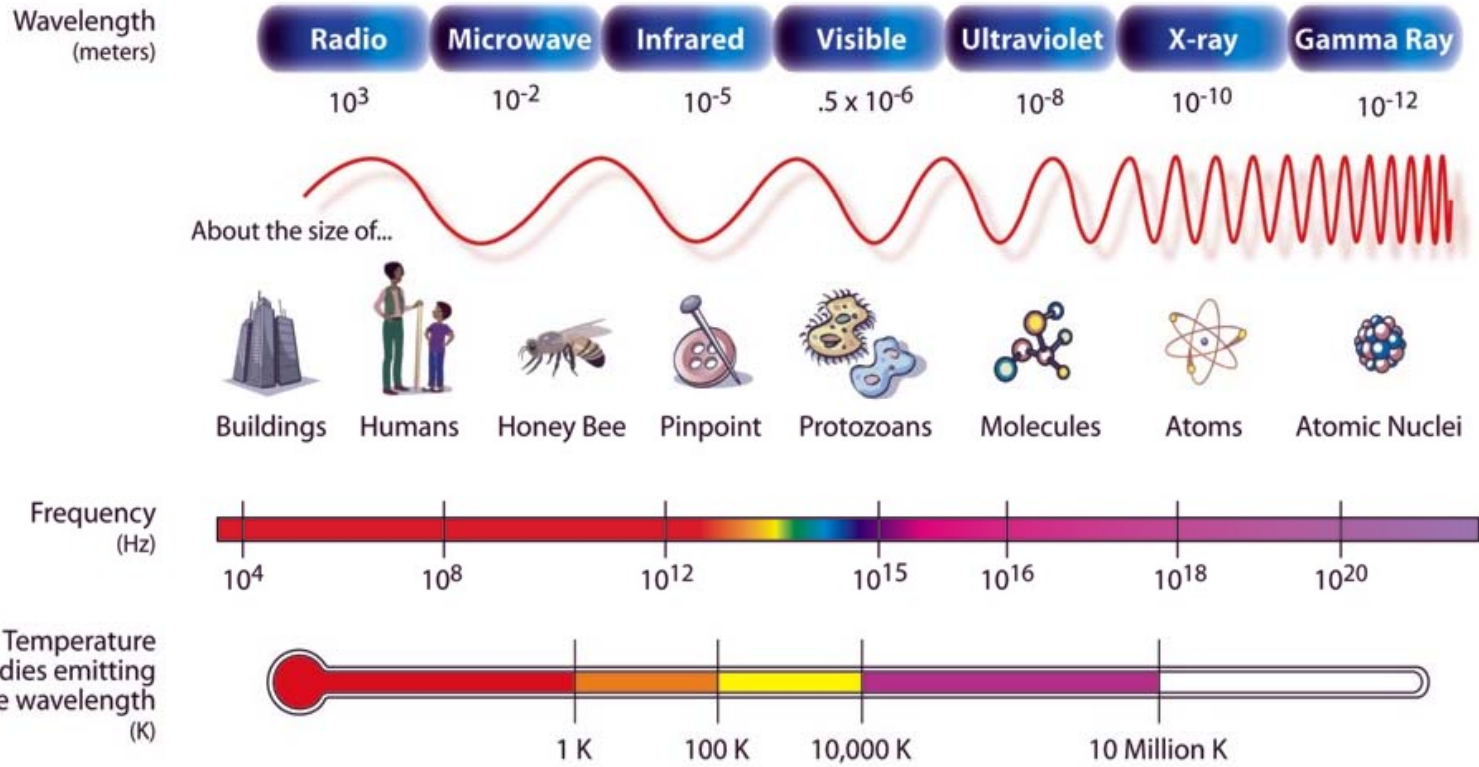
Science Drivers → Requirements → Implementation

CTA Design & Performance → Scientific Capabilities

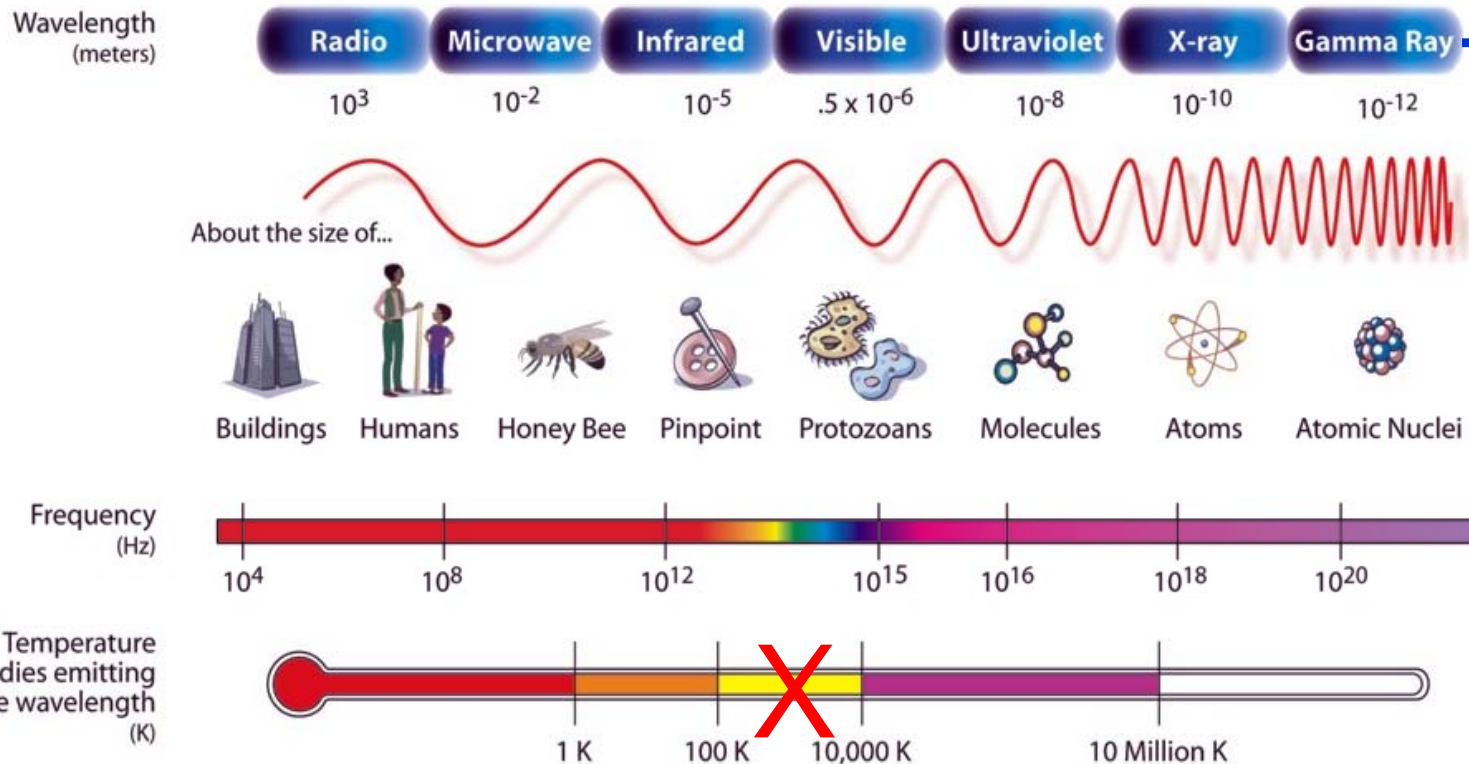
Present status (2017): sites, timeline, etc.

- **Summary**

# Spectrum of Light



# High Energy Light



**Very High Energy (VHE)**

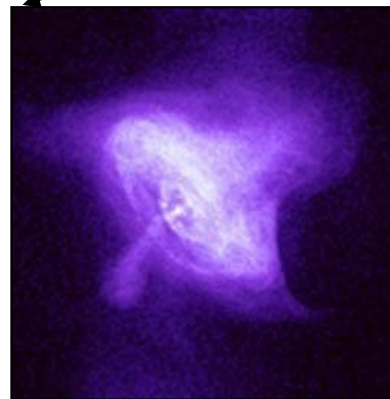
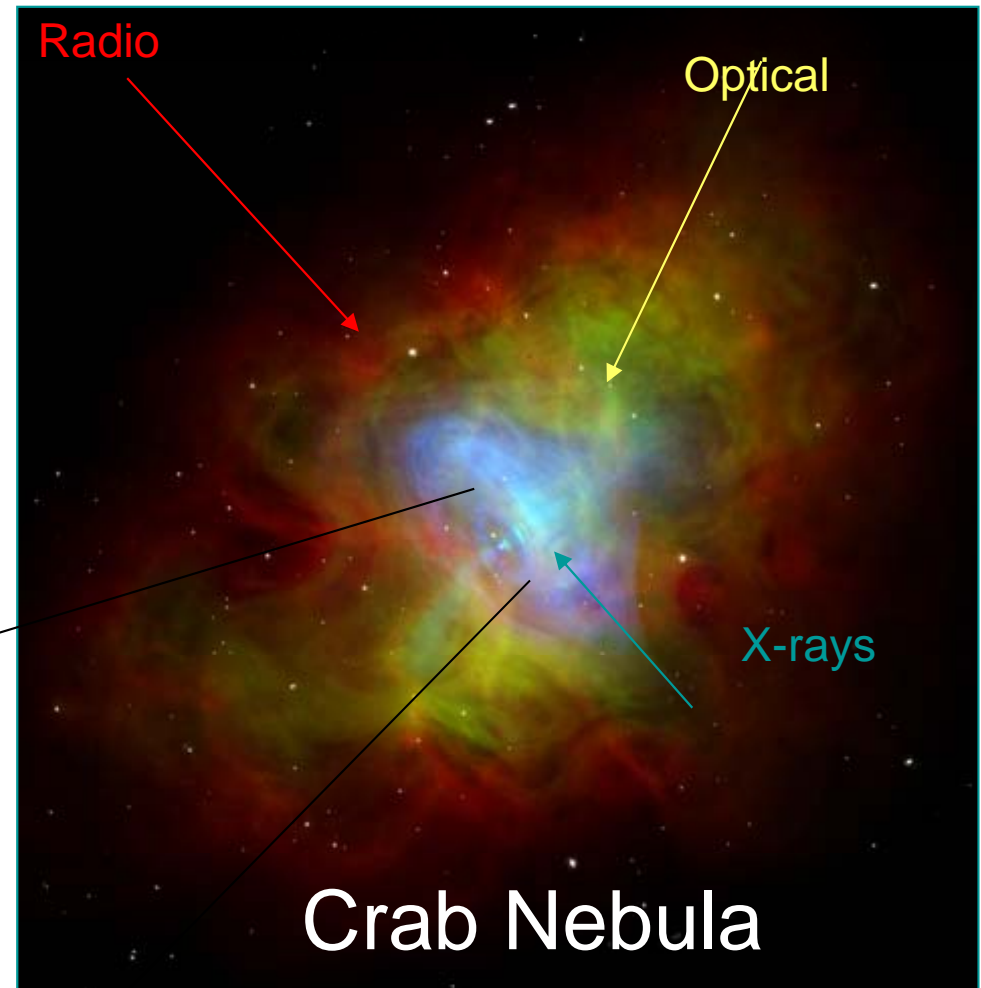
Energy (eV)

1	$10^3$	$10^6$	$10^9$	$10^{12}$	$10^{15}$
	keV	MeV	GeV	TeV	PeV



# A New Astronomy

- Before 1930's – Astronomy only used visible light.
- New wavebands (radio, IR, X-ray,  $\gamma$ -ray) change our picture of the universe.
- Other messengers: neutrinos & grav. waves.

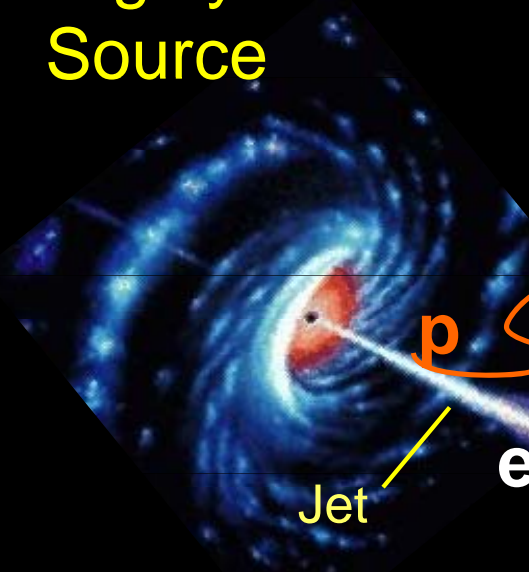


Crab Pulsar (X-rays)

**Also a source of VHE  $\gamma$ -rays !**

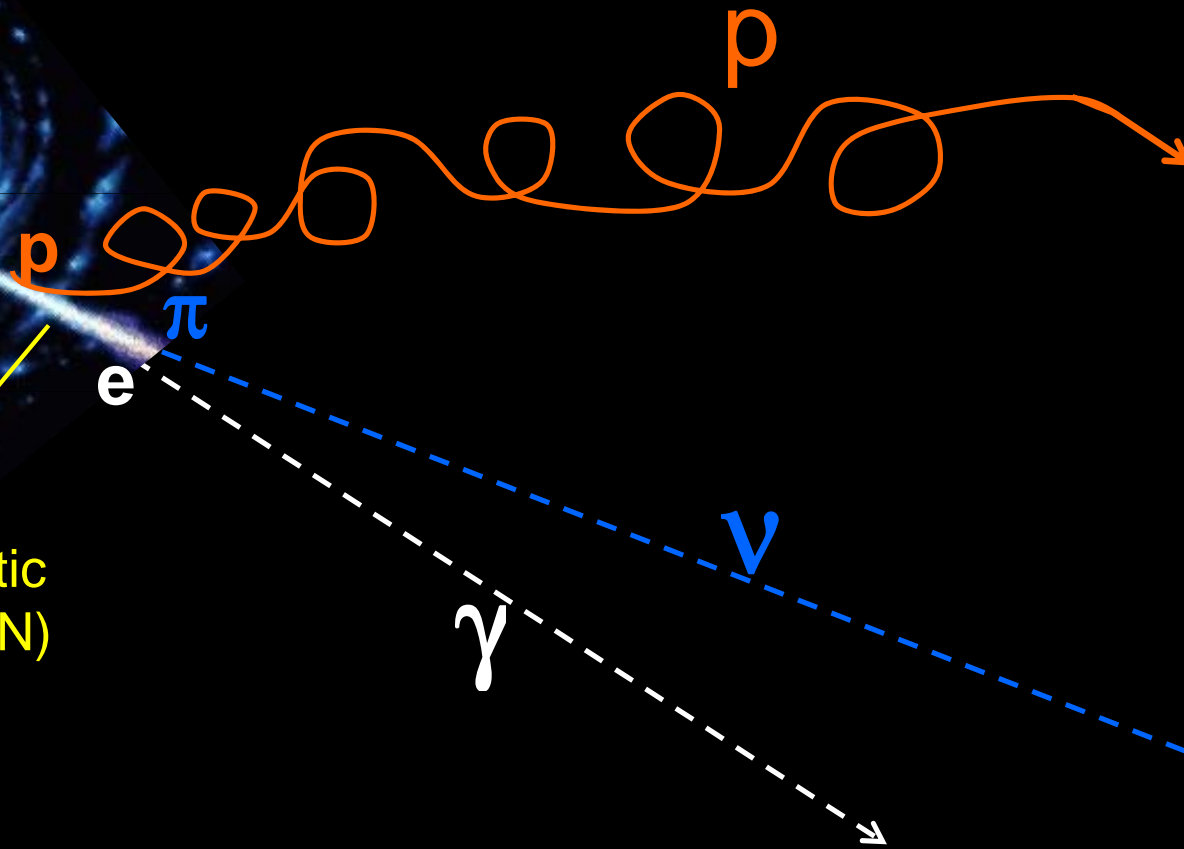
# Very High Energy (VHE) Astrophysics

Highly Non-Thermal Source

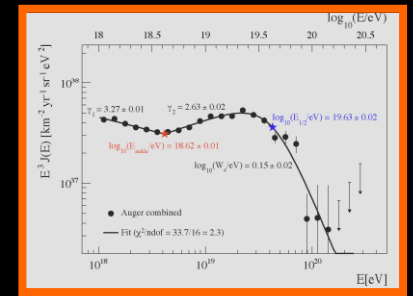


Active Galactic Nucleus (AGN)

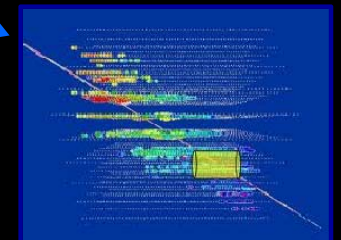
$\gamma$ -rays provide, by far, the most direct information



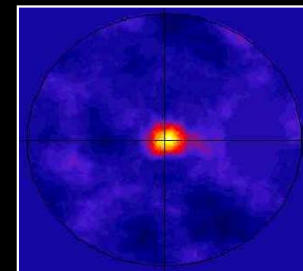
EeV Cosmic Rays



PeV Neutrinos

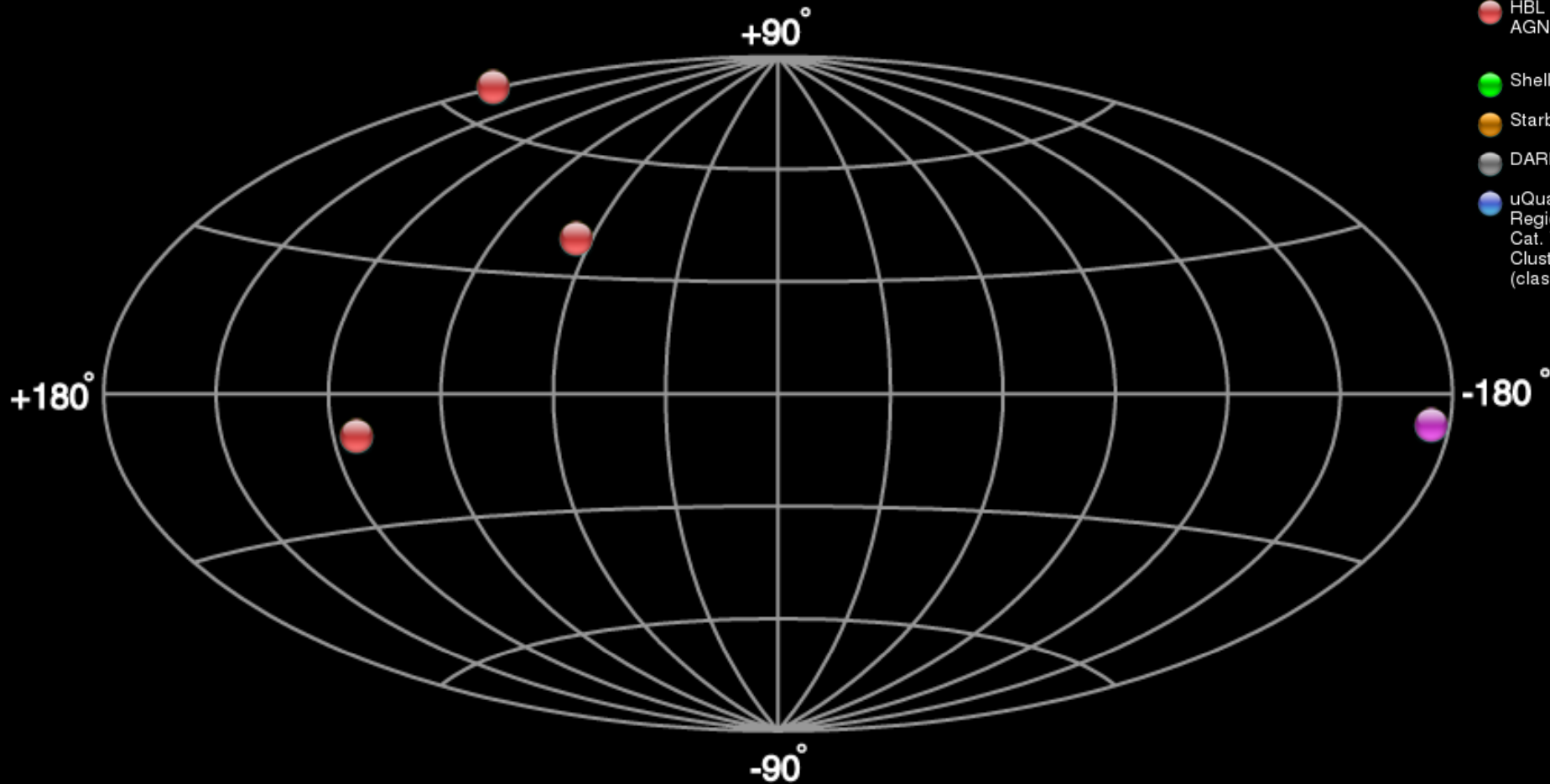


GeV/TeV  $\gamma$ -rays



# VHE $\gamma$ -ray Sky c1997

4 sources

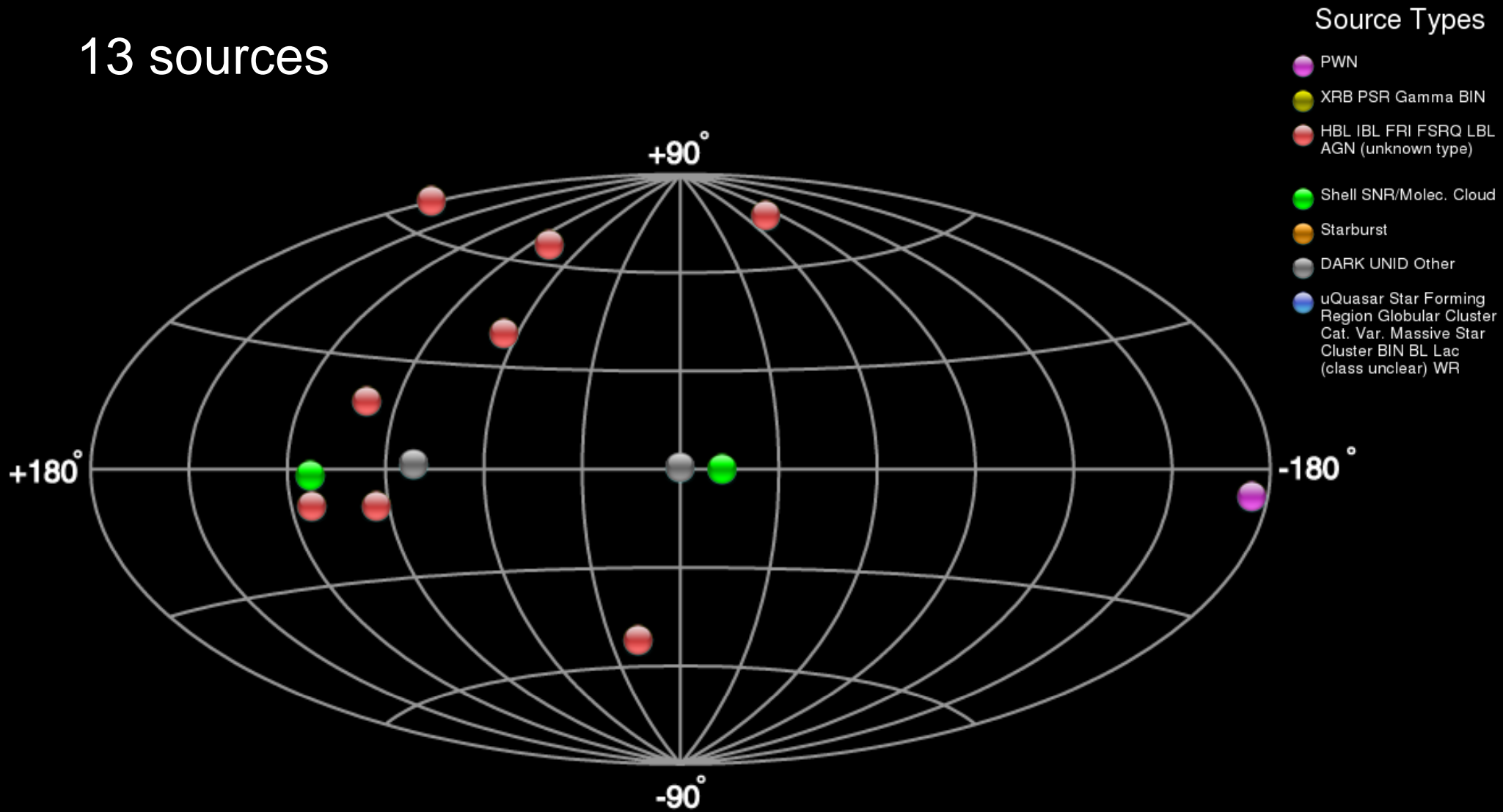


## Source Types

- PWN
- XRBB PSR Gamma BIN
- HBL IBL FRI FSRQ LBL  
AGN (unknown type)
- Shell SNR/Molec. Cloud
- Starburst
- DARK UNID Other
- uQuasar Star Forming  
Region Globular Cluster  
Cat. Var. Massive Star  
Cluster BIN BL Lac  
(class unclear) WR

# VHE $\gamma$ -ray Sky c2006

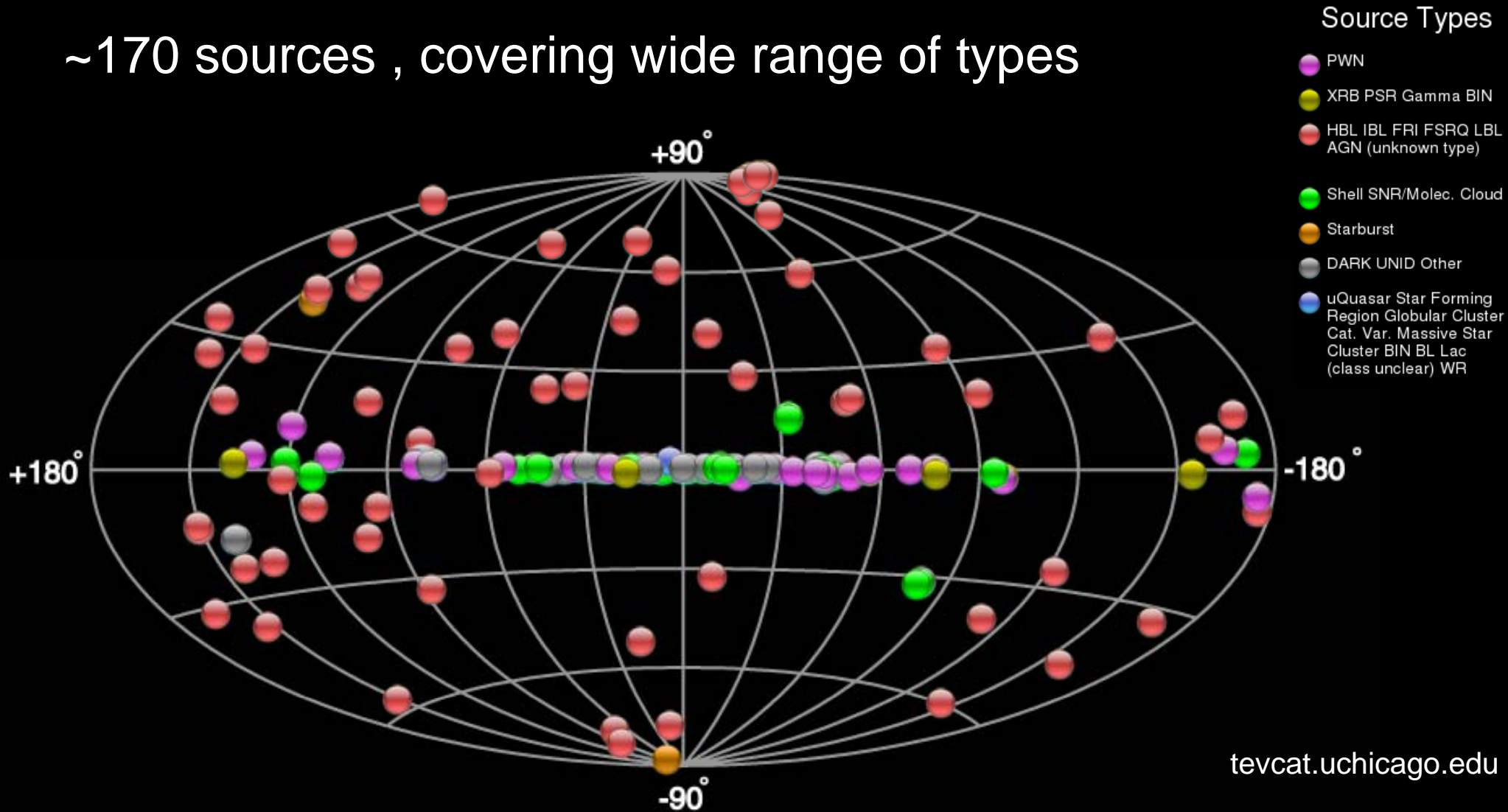
13 sources





# VHE $\gamma$ -ray Sky c2017

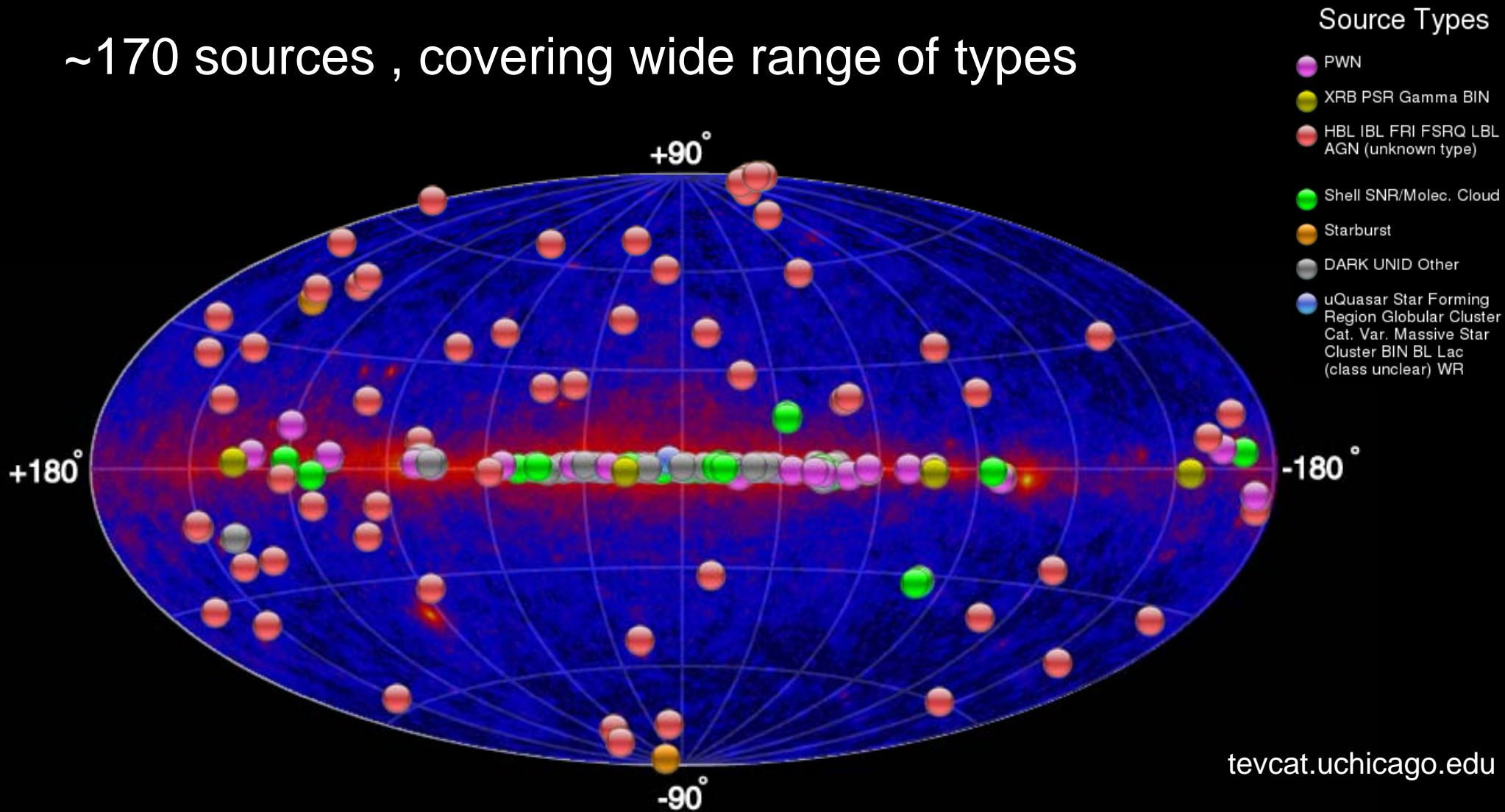
~170 sources , covering wide range of types



Detailed source information: Spectra, Images, Variability, MWL ...

# HE + VHE $\gamma$ -ray Sky c2017

~170 sources , covering wide range of types



- Wide variety of HE/VHE sources in our Galaxy and outside
- Many sources not clearly identified with known objects

# Three Selected Science Topics

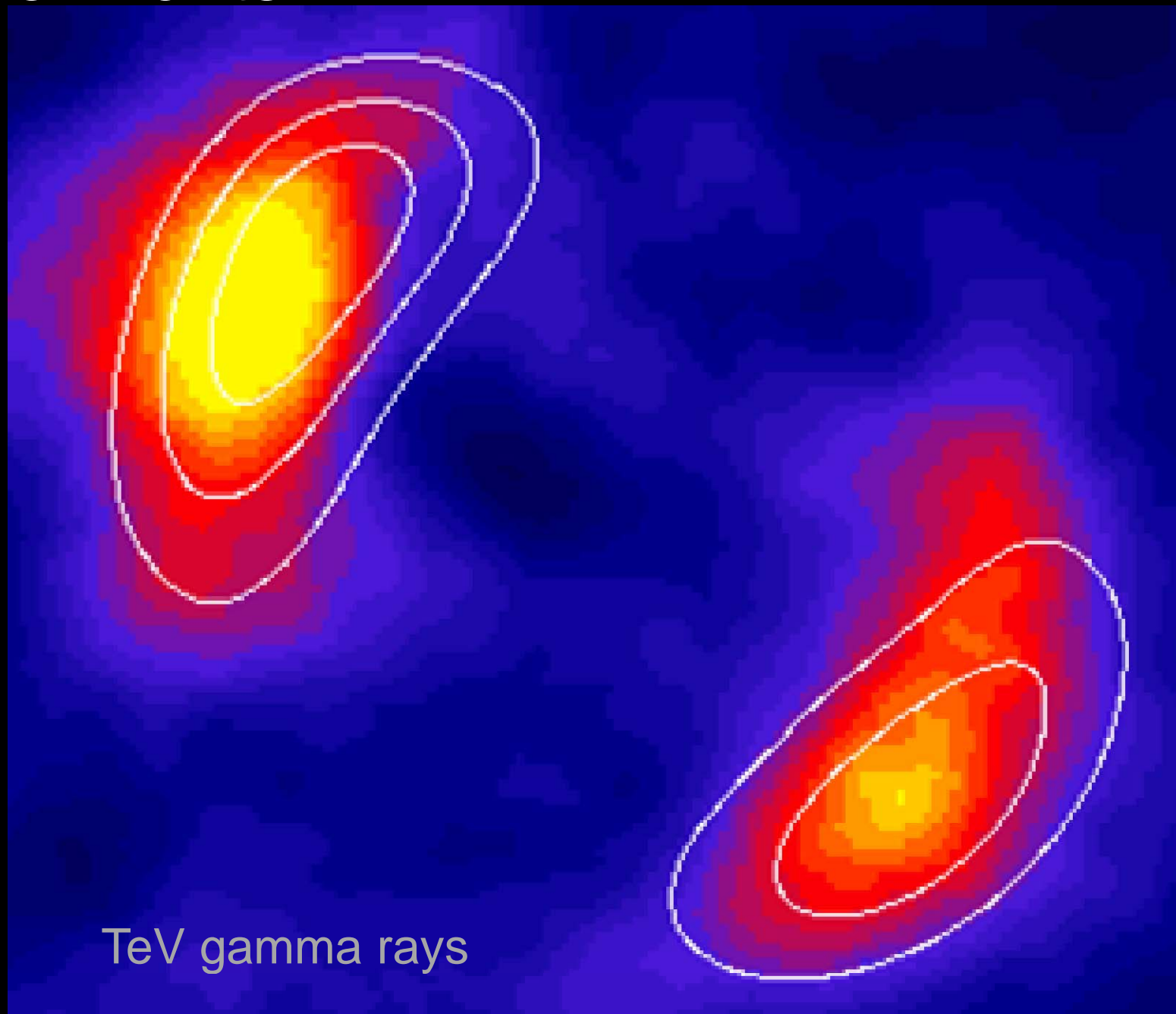
- Supernova remnants & origin of cosmic rays
- Active Galactic Nuclei (AGN)
- Galactic Center & Dark Matter

# Supernova Remnants

## SN 1006

Blue: X-ray  
Yellow: Optical  
Red: Radio

(Credit: X-ray:  
NASA/CXC/Rutgers/G. Cassam-  
Chenai, J. Hughes et al.; Radio:  
NRAO/AUI/NSF/GBT/VLA/Dyer,  
Maddalena & Cornwell; Optical:  
Middlebury College/F. Winkler,  
NOAO/AURA/NSF/CTIO Schmidt  
& DSS)



← 0.4° →



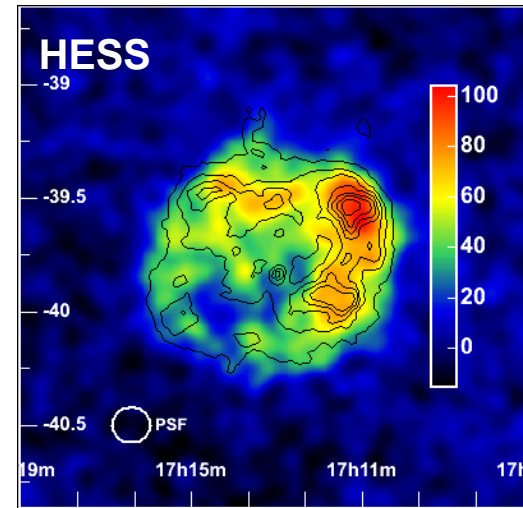
# Supernova Remnants (SNRs)

“Standard Model” for the origin of the cosmic rays:

- Expanding shell of SNR & shock front sweeps up ISM material.
- Acceleration of particles via diffusive shock acceleration.
- Can supply and replenish CR's if  $\epsilon \sim 5\text{-}10\%$ .

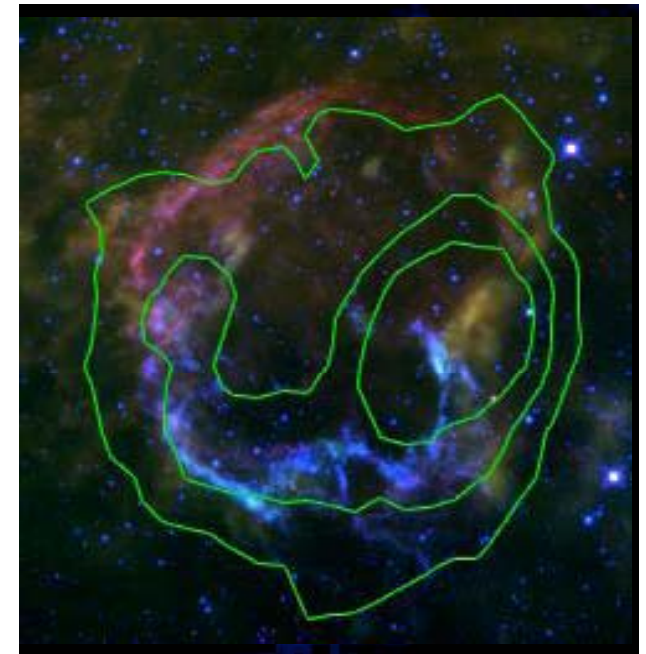
Good model ... is it right ?

We don't yet know if the model is right or not, but there has been considerable progress in the last few years.



**RXJ 1713-3946**  
Age = 1600 y  
D = ~1 kpc

**IC 443**  
Age ~ 30 ky  
D ~ 0.8kpc

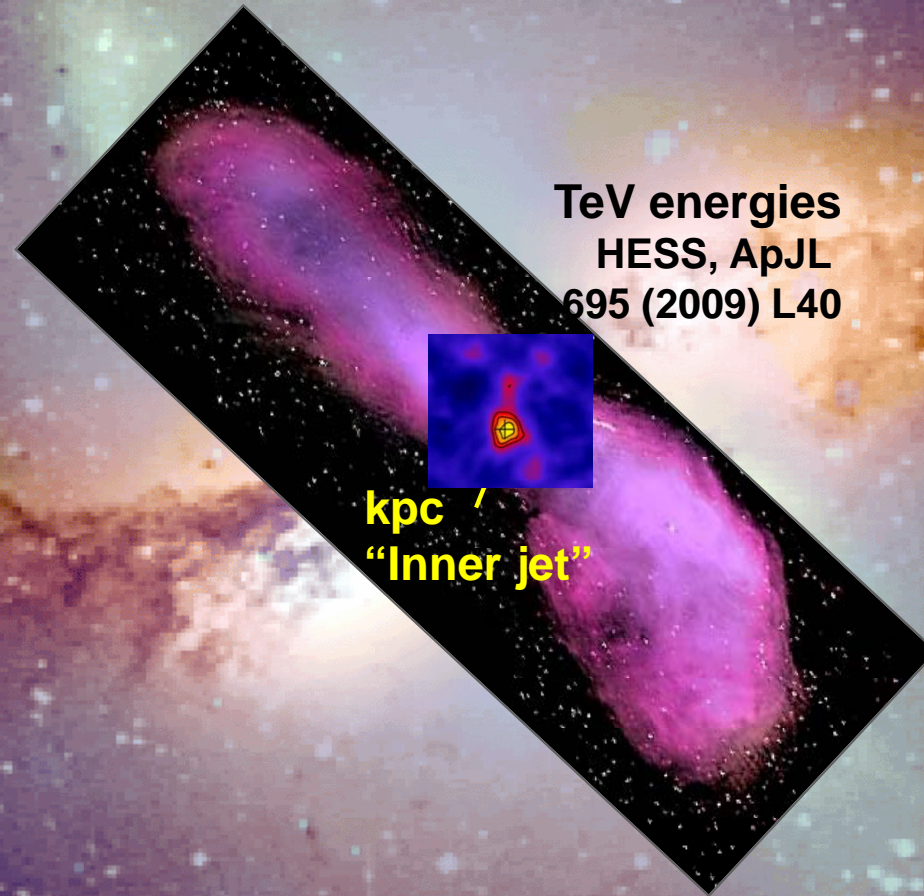


**WISE –**  
22, 12, 4.6  $\mu\text{m}$



# Active galactic nuclei and their jets

Radio



TeV energies  
HESS, ApJL  
695 (2009) L40

kpc /  
"Inner jet"

## Cen-A

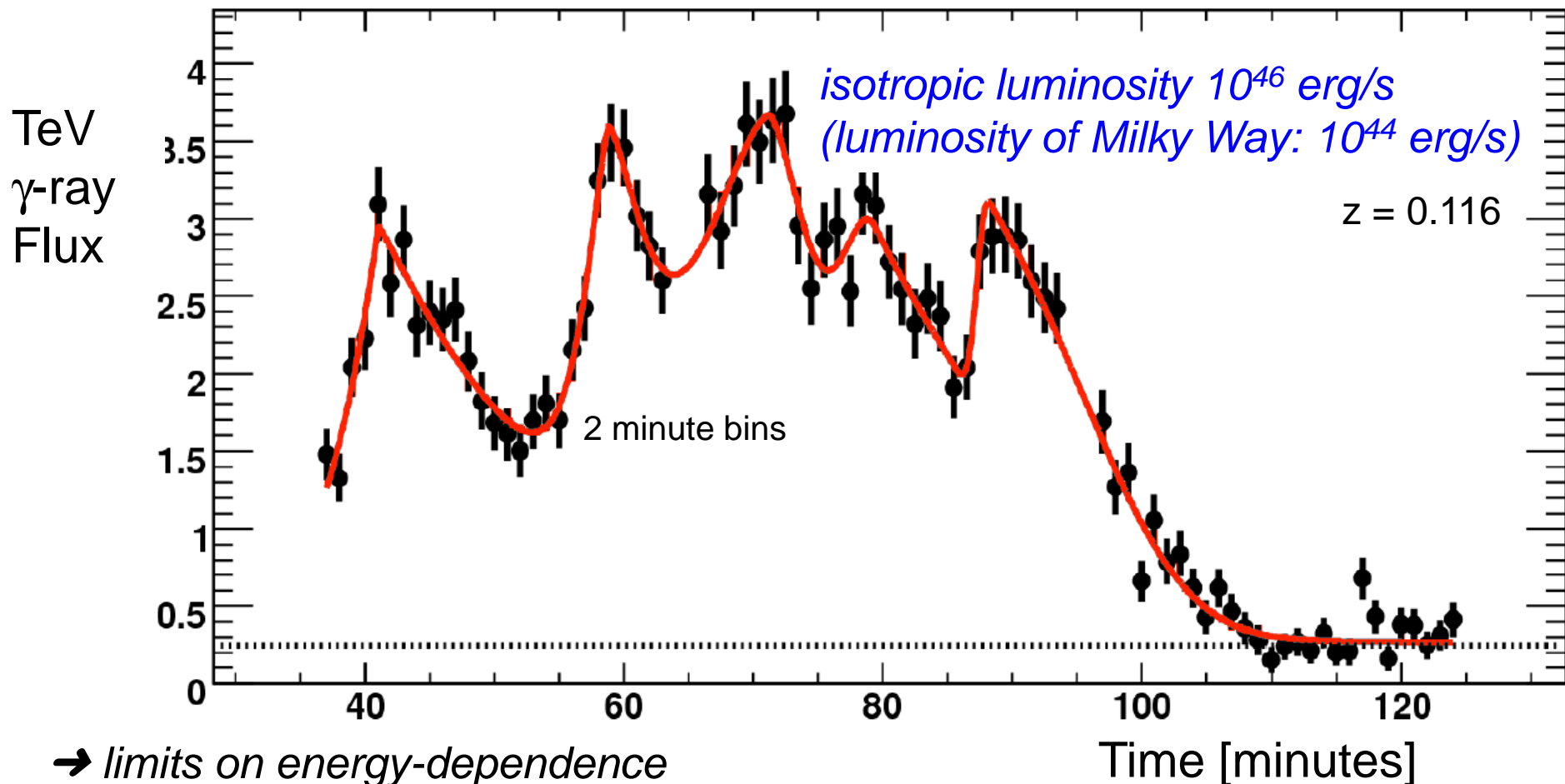
Nearest AGN,  $d \sim 4$  Mpc  
Radio lobes  $3-4^\circ$ ,  $\sim 300$  kpc



# AGN that Point to Us

“Blazars”: AGN with jets pointed to us  
Remarkable variability !

PKS 2155-304 flare  
in TeV  $\gamma$ -rays

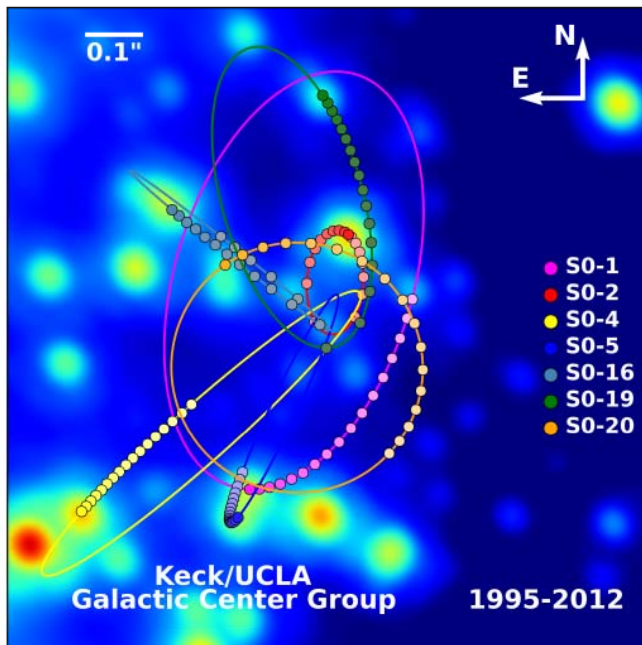


→ limits on energy-dependence  
of speed of light

→ Study transparency of universe (EBL)

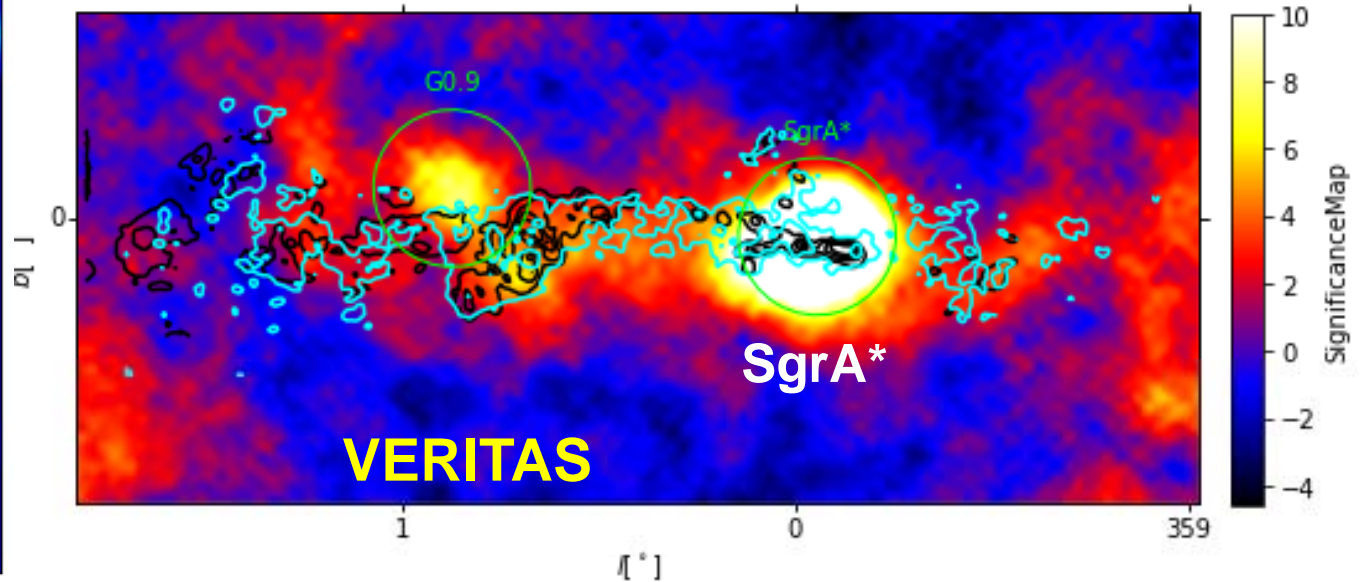
# Galactic Center – A Mystery

## Infrared



Ghez et al., 2012  
1'' x 1''

## TeV $\gamma$ -rays

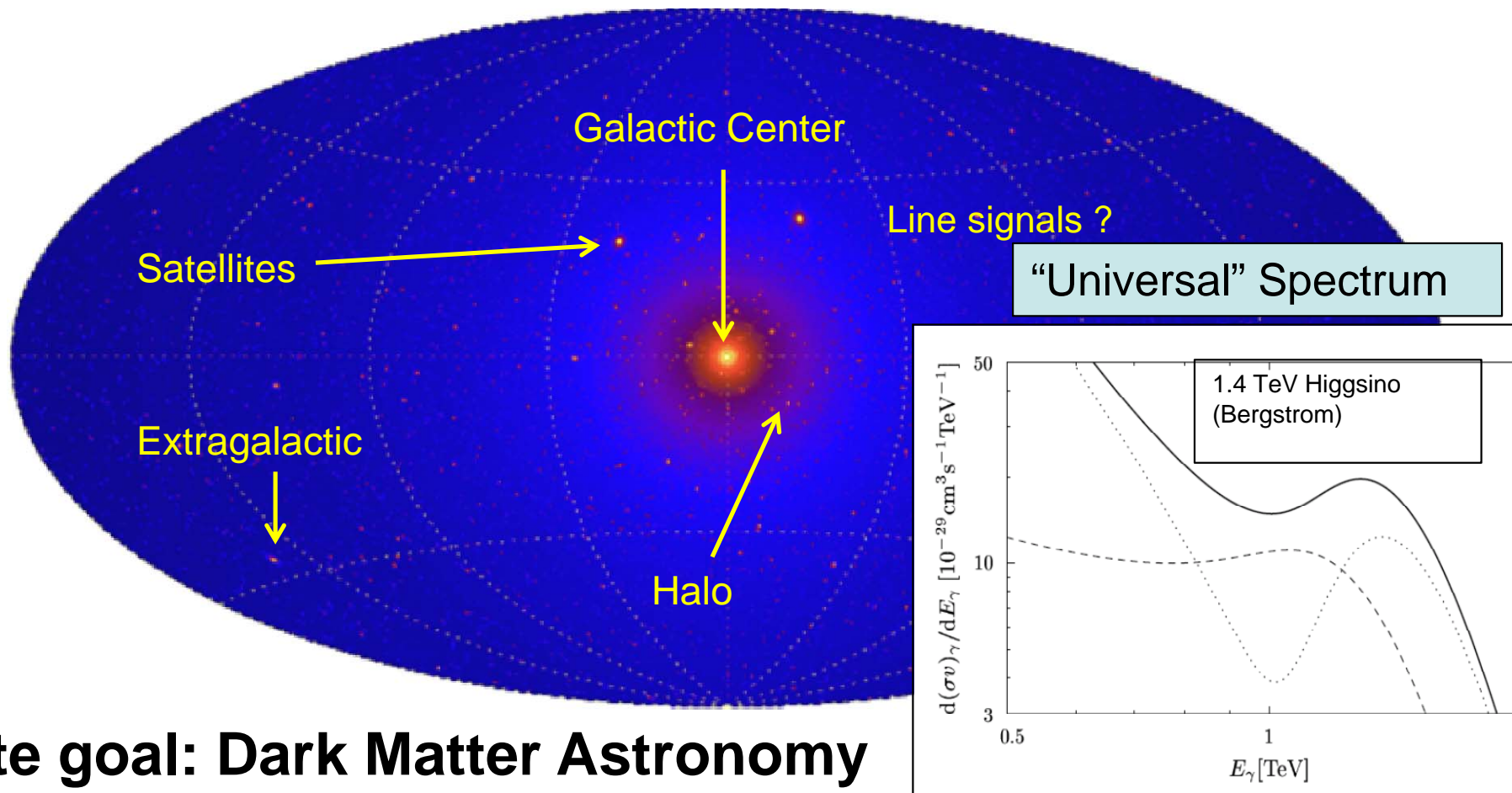
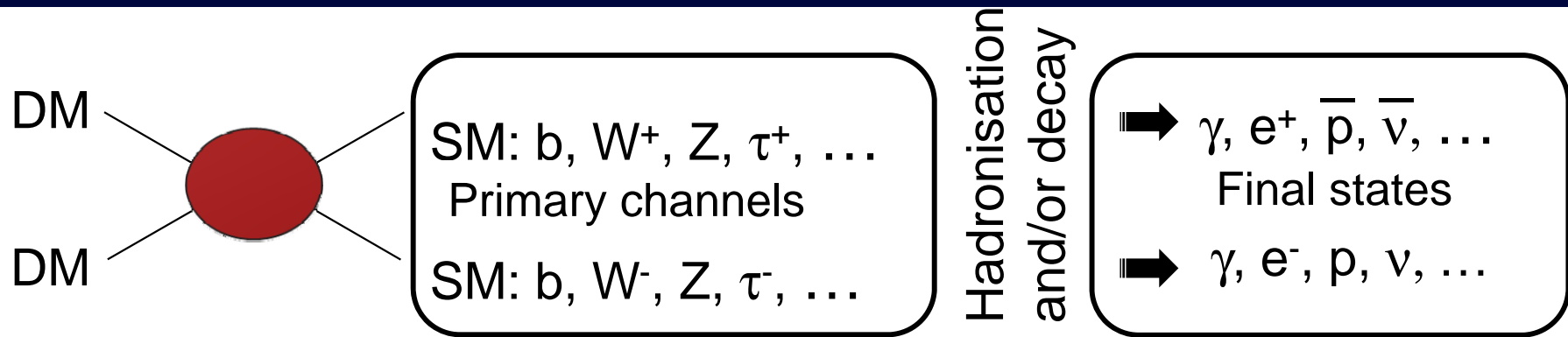


A, Archer et al.  
VERITAS Coll.  
(2015)  
1° x 2°

## TeV Emission is:

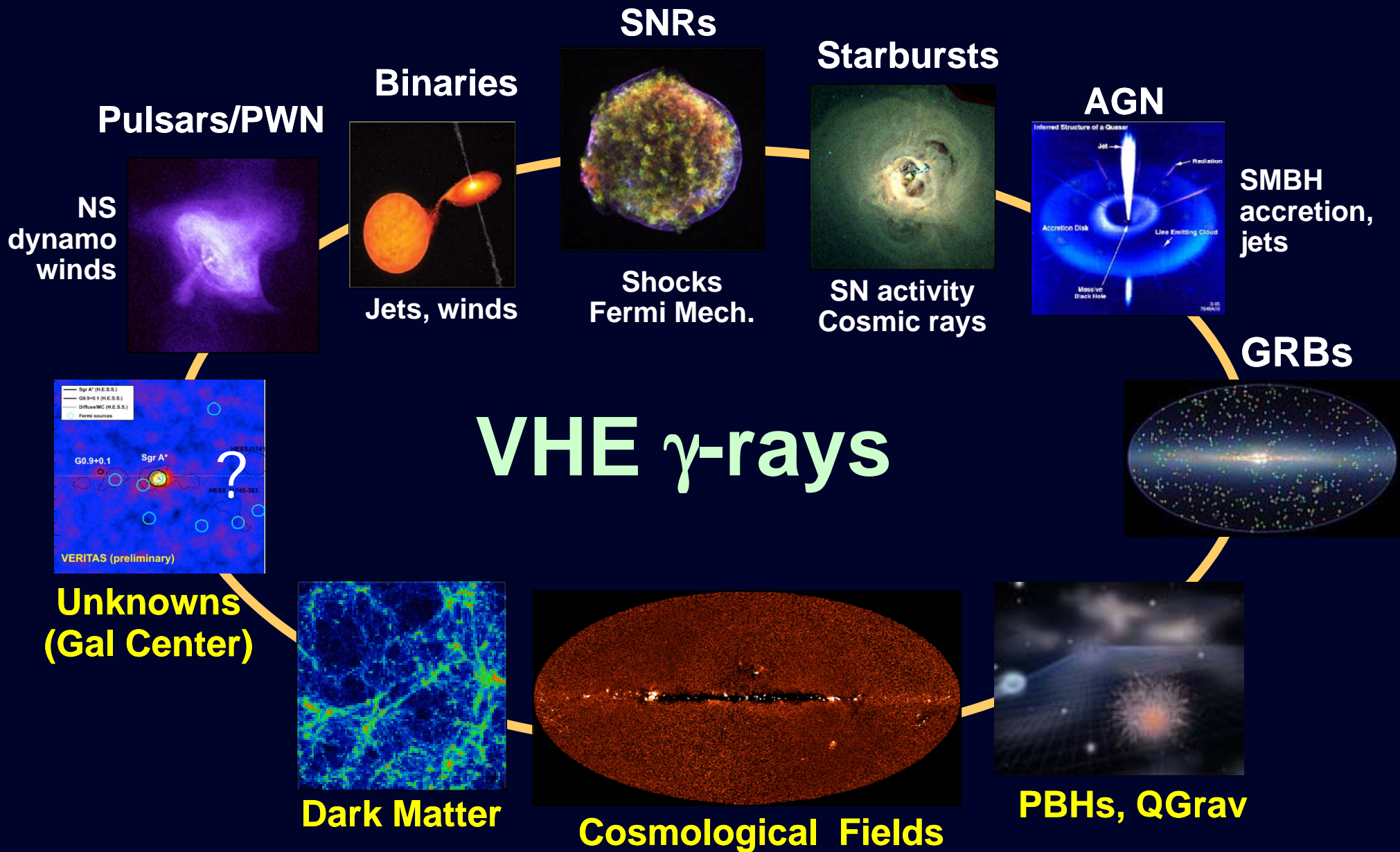
- Intense and highly non-thermal
- completely unexpected
- not understood !

# (Indirect) Dark Matter Detection



Ultimate goal: Dark Matter Astronomy

# Exploring the non-thermal Universe “ASTRO”



Probing New Physics at GeV/TeV scale “PARTICLE”



# **Experimental Technique & Planning for the Future**

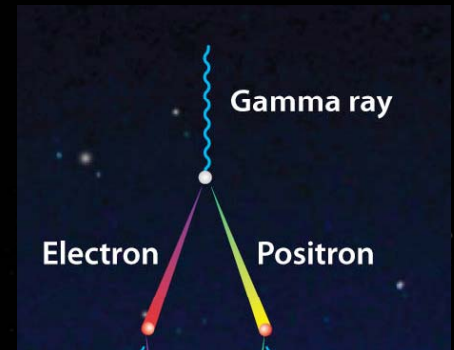
# Fermi Large Area Telescope (LAT)

30 MeV-300 GeV

Anti-Coincidence  
Shield

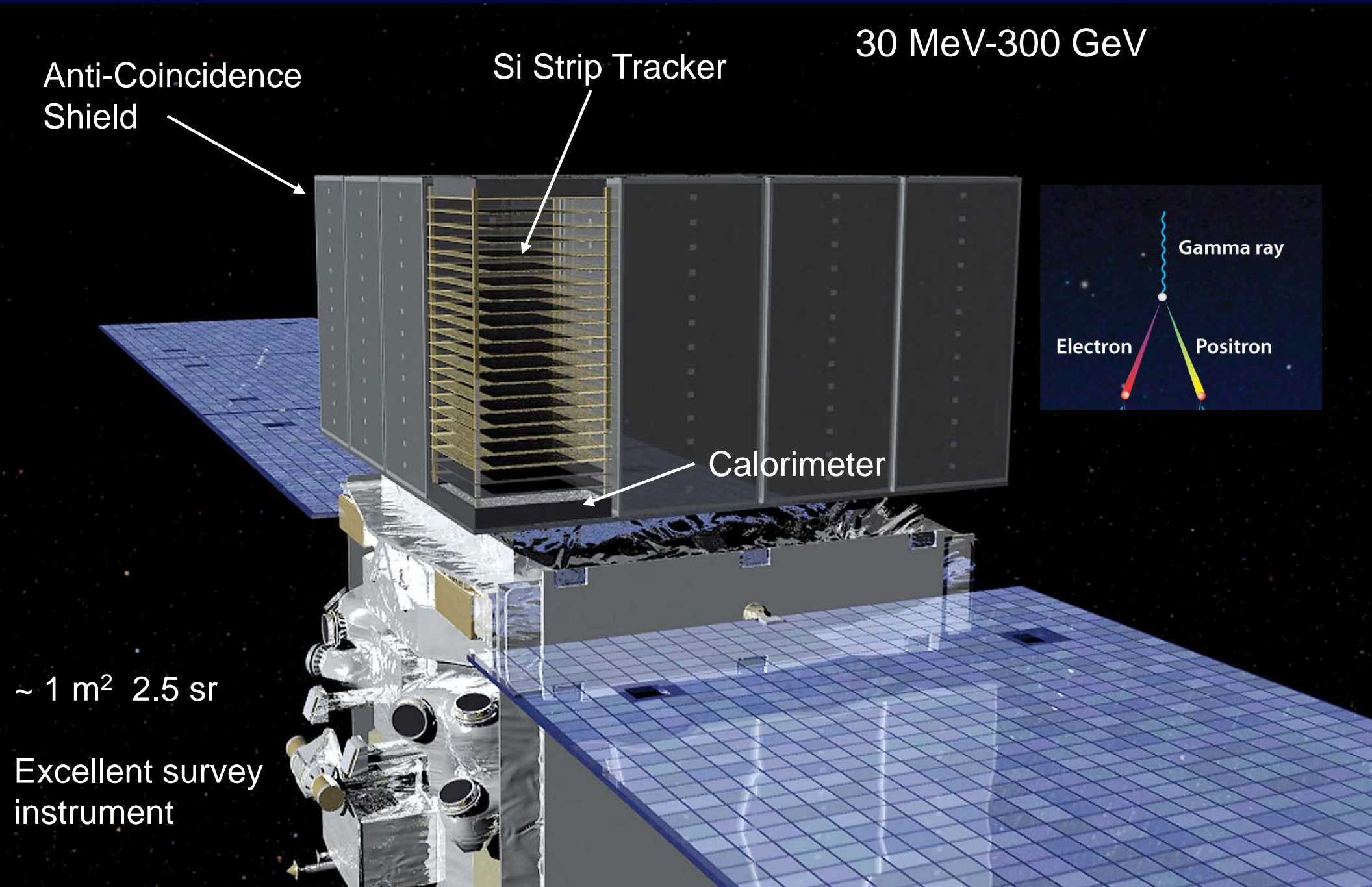
Si Strip Tracker

Calorimeter



~ 1 m<sup>2</sup> 2.5 sr

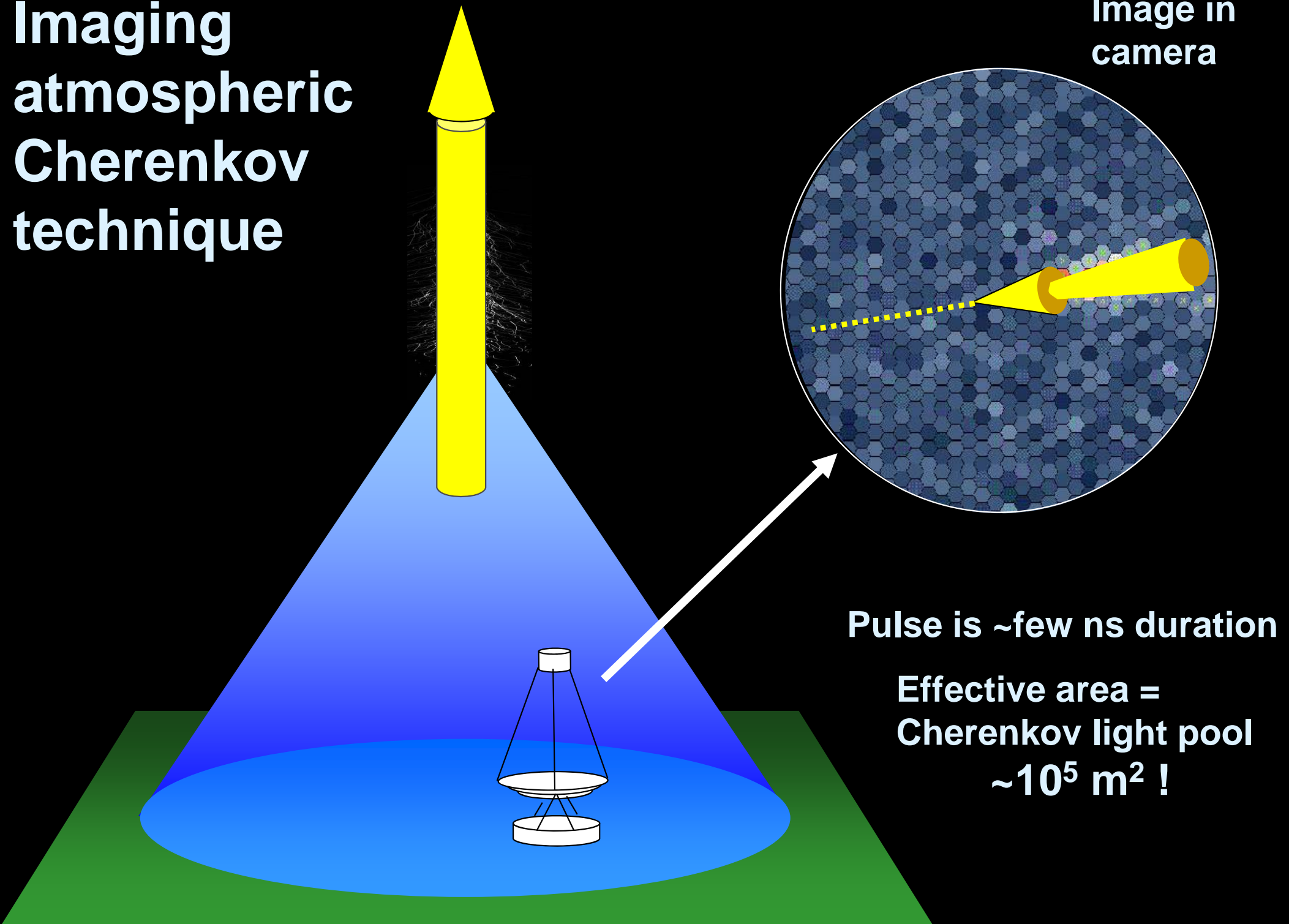
Excellent survey  
instrument





# Imaging atmospheric Cherenkov technique

Image in  
camera

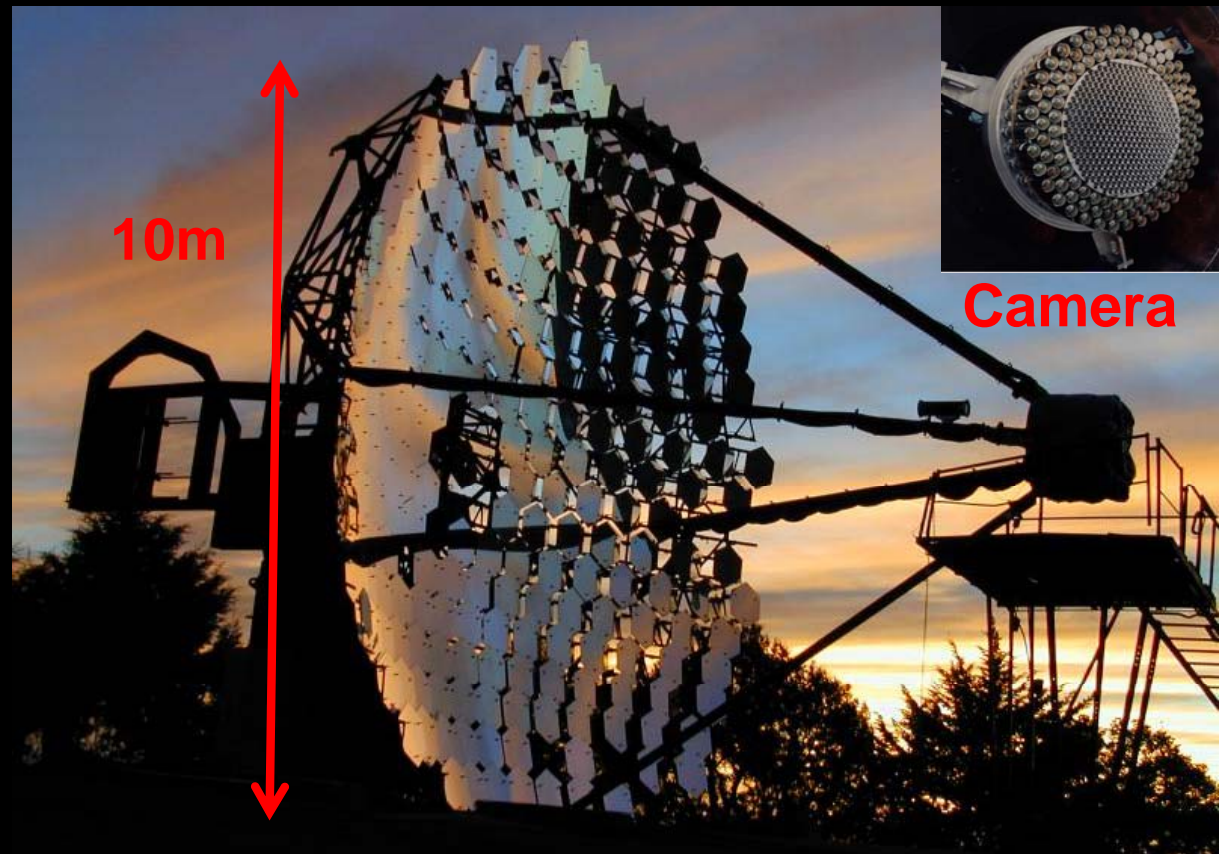




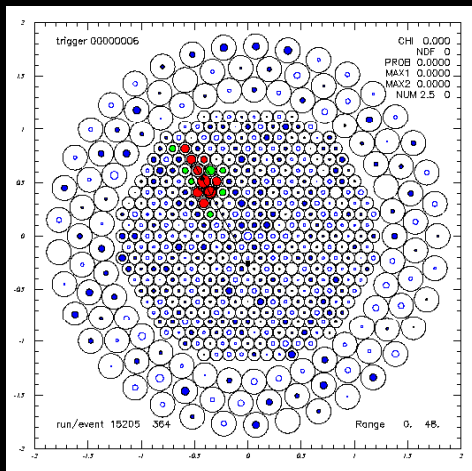
# Whipple 10m $\gamma$ -ray Telescope (1968-2011)

Mt. Hopkins, AZ USA

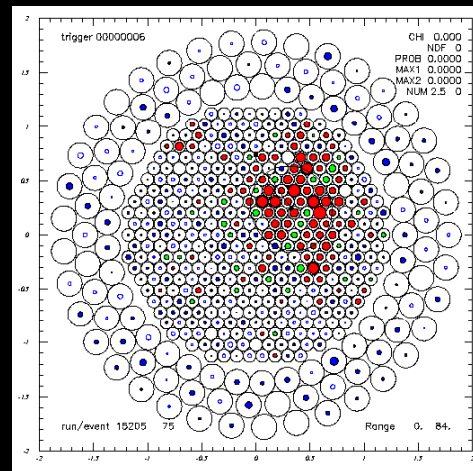
- Pioneered use of Imaging
- Made first source detection.  
(Crab Nebula in ~90 hours)



$\gamma$ -ray



cosmic ray





# Imaging atmospheric Cherenkov arrays

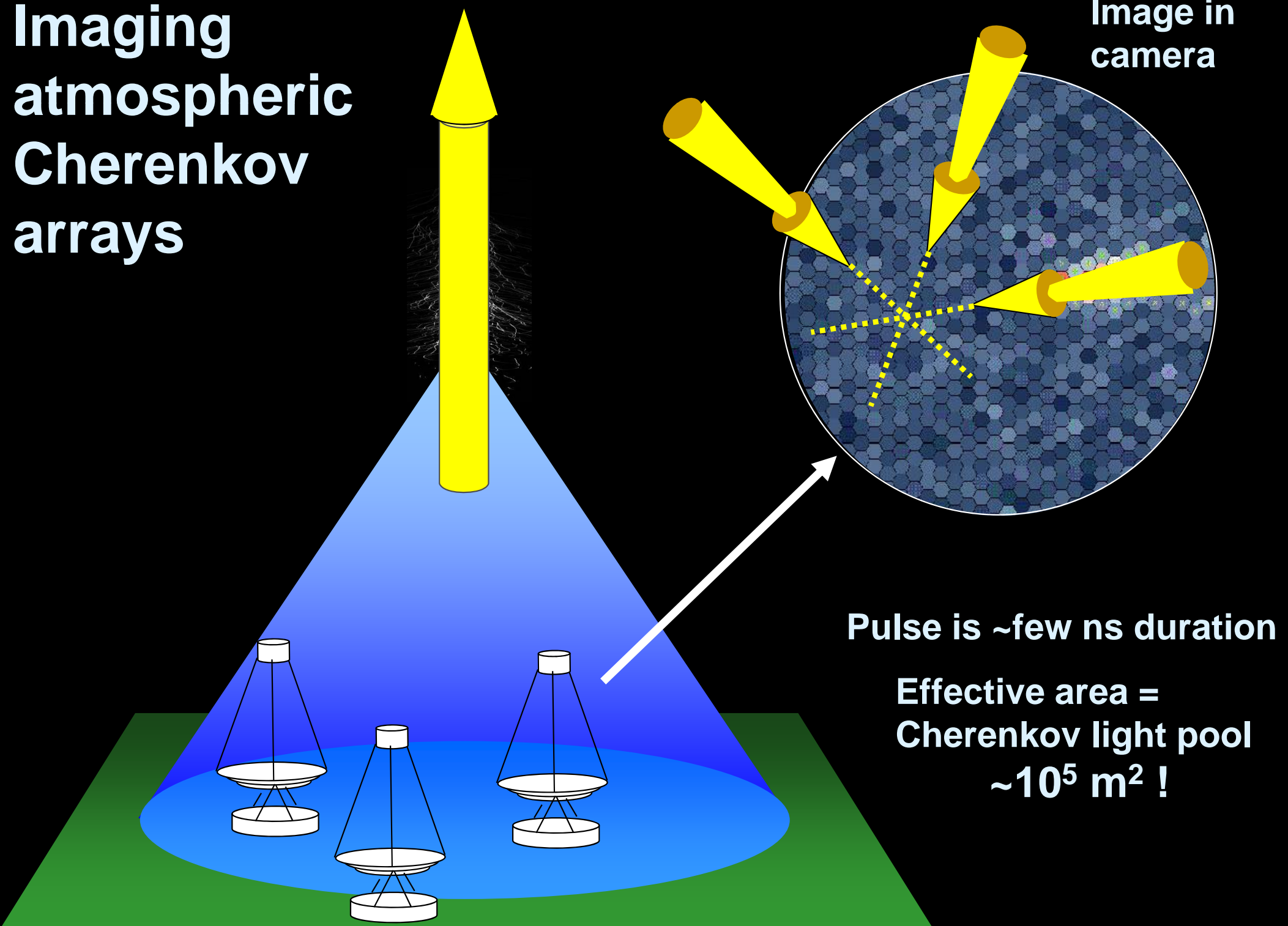
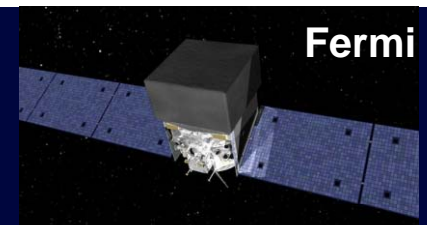


Image in camera

Pulse is ~few ns duration

Effective area =  
Cherenkov light pool  
~10<sup>5</sup> m<sup>2</sup> !

# VHE Telescopes (2017)



VERITAS

MAGIC

ARGO / YBJ

HAWC

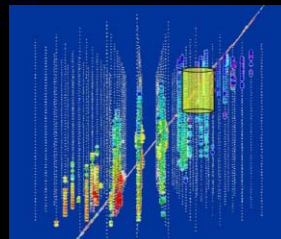


HESS

HESS



IceCube



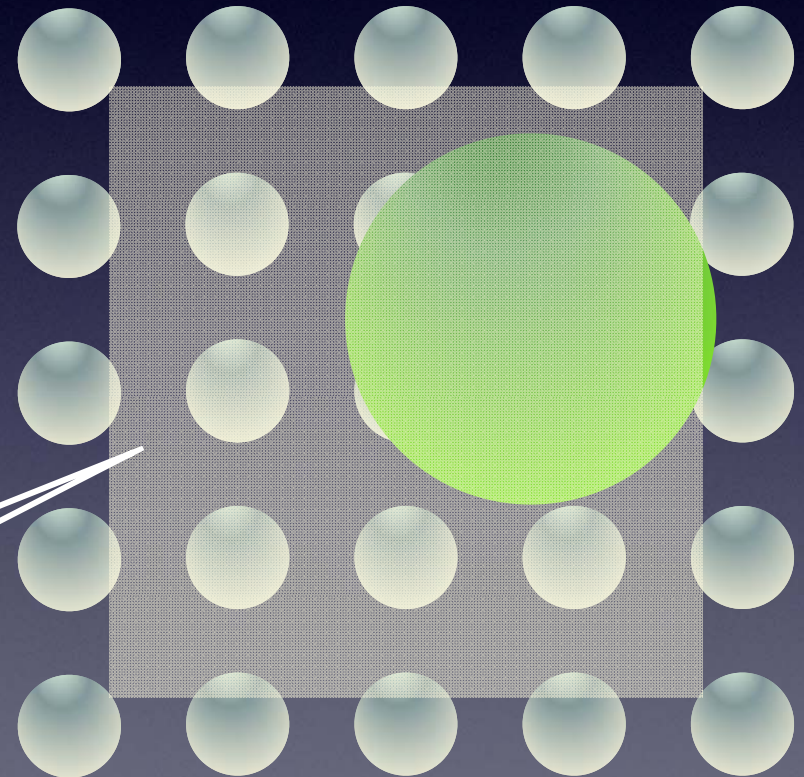


# From current arrays to CTA

*Light pool radius*  
 $R \approx 100-150\text{m}$   
 $\approx$  typical telescope Spacing

*Sweet spot for best triggering & reconstruction...  
most showers miss it!*

- ✓ Large detection Area
- ✓ More Images per shower
- ✓ Lower trigger threshold



**What we know, based on current instruments:**

**Great scientific potential exists in the VHE domain**

- *Expect many more sources & deeper probes for new physics*

**IACT Technique is very powerful**

- *Have not yet reached its full potential → large Cherenkov array*

**Exciting science in both Hemispheres**

- *Argues for an array in both S and N*

**Open Observatory → Substantial reward**

- *Open data/access, MWL connections to get the best science*

**International Partnerships required by scale/scope**

- *Project must develop the instrument and the observatory*

# Requirements & Drivers

**Energy coverage  
down to 20 GeV**  
*(Discovery domain:  
GRBs, Dark Matter)*

**Energy coverage  
up to 300 TeV**  
*(Pevatrons, hadron  
acceleration)*

**Good energy  
resolution, ~10-15%:**  
*(Lines, cutoffs)*

**Large Field of view 8-10°**  
*(Surveys, extended  
sources, flares)*

**Rapid Slew (20 s)  
to catch flares:**  
*(Transients)*

**10x Sensitivity &  
Collection Area**  
*(Nearly every topic)*

**Angular resolution < 0.1°  
above most of E range**  
*(Source morphology)*



# Science Themes

## Theme 1: Cosmic Particle Acceleration

- How and where are particles accelerated?
- How do they propagate?
- What is their impact on the environment?

## Theme 2: Probing Extreme Environments

- Processes close to neutron stars and black holes?
- Processes in relativistic jets, winds and explosions?
- Exploring cosmic voids

## Theme 3: Physics Frontiers – beyond the SM

- What is the nature of Dark Matter? How is it distributed?
- Is the speed of light a constant for high energy photons?
- Do axion-like particles exist?



# CTA Design (S array)

Science Optimization under budget constraints

## Low energies

Energy threshold 20-30 GeV

23 m diameter

4 telescopes

**(LST's)**



## Medium energies

100 GeV – 10 TeV

9.5 to 12 m diameter

25 single-mirror telescopes

up to 24 dual-mirror telescopes

**(MST's/SCTs)**



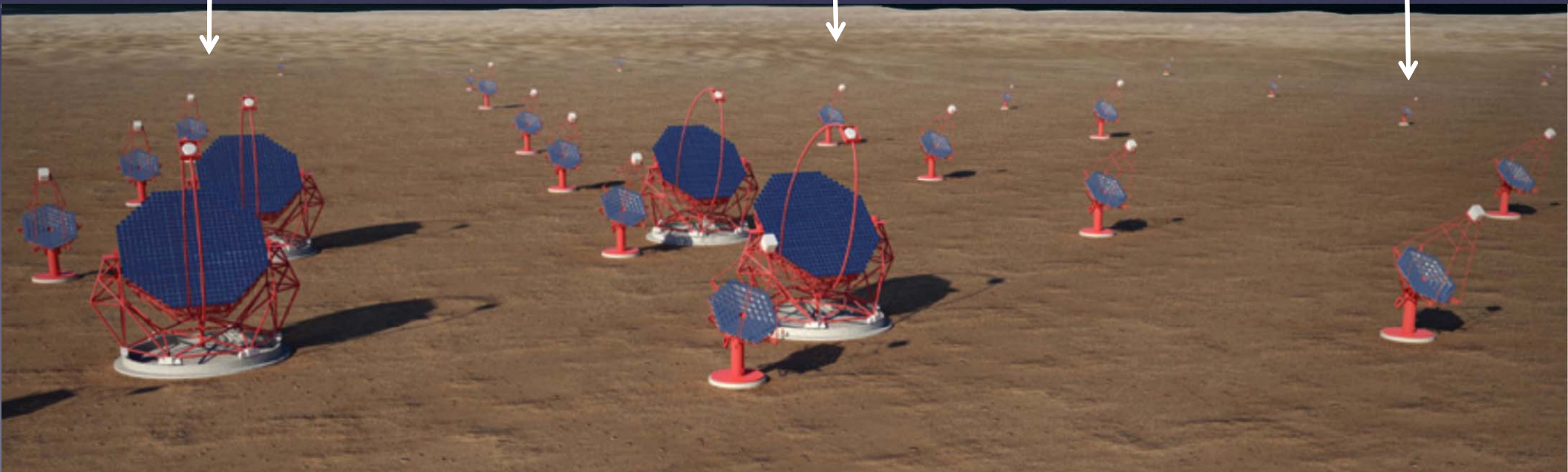
## High energies

10 km<sup>2</sup> area at few TeV

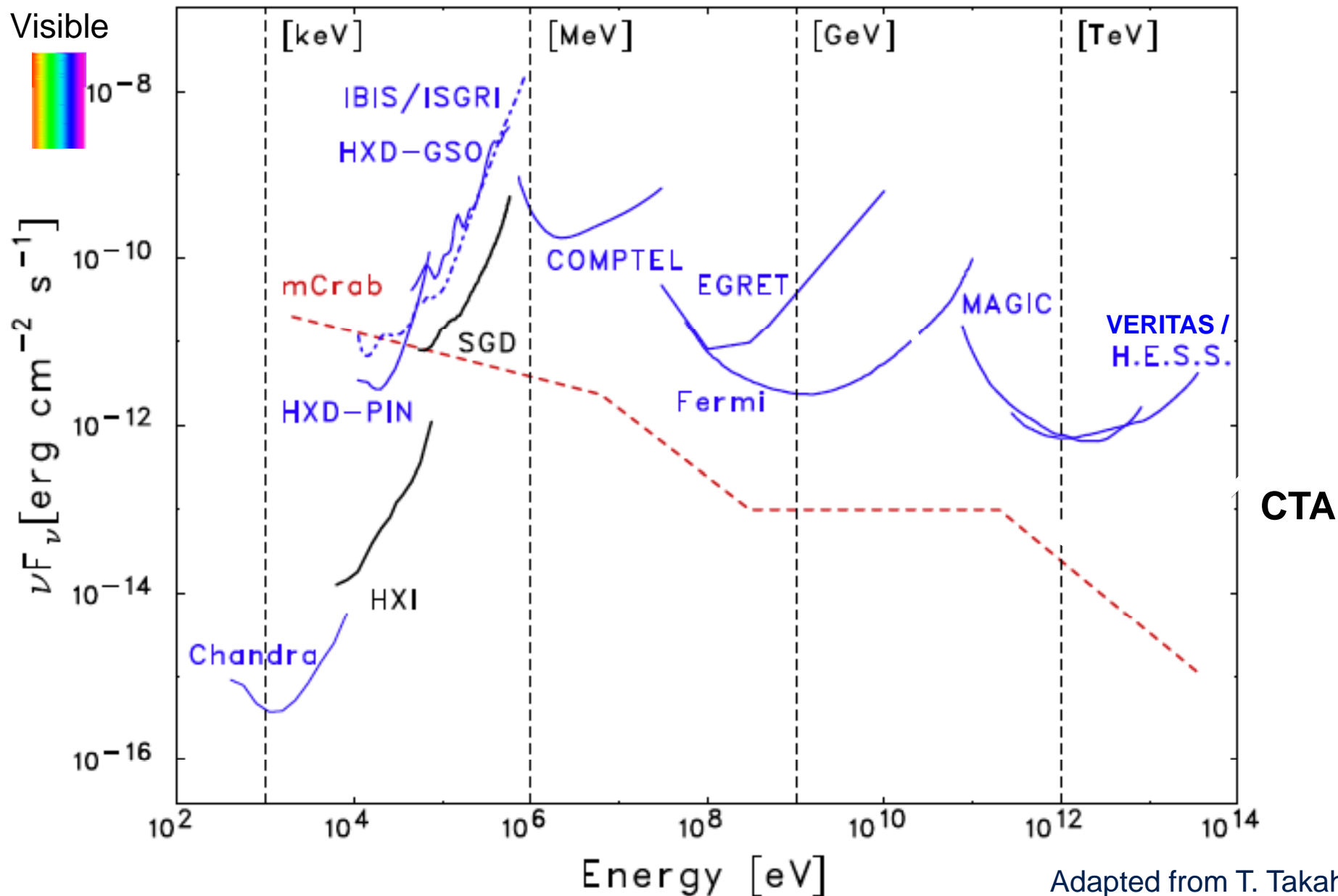
3 to 4m diameter

70 telescopes

**(SST's)**



# CTA Sensitivity in Context



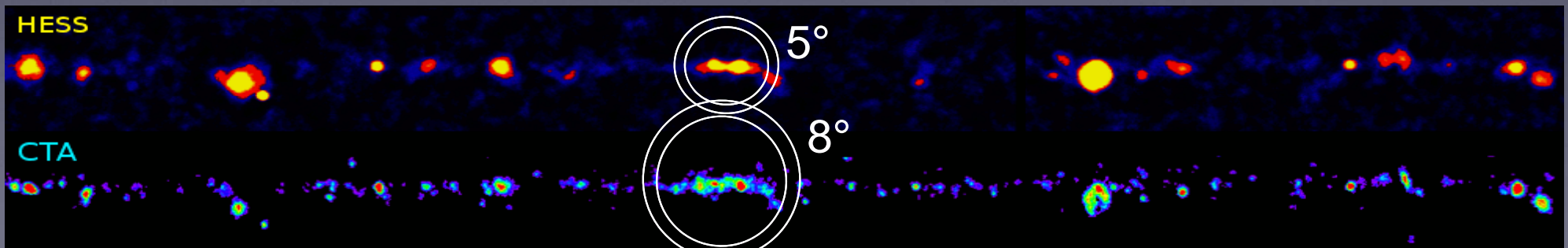
# Galactic Discovery Reach

Current Galactic  
VHE sources  
(with distance  
estimates)

HESS/  
VERITAS

CTA

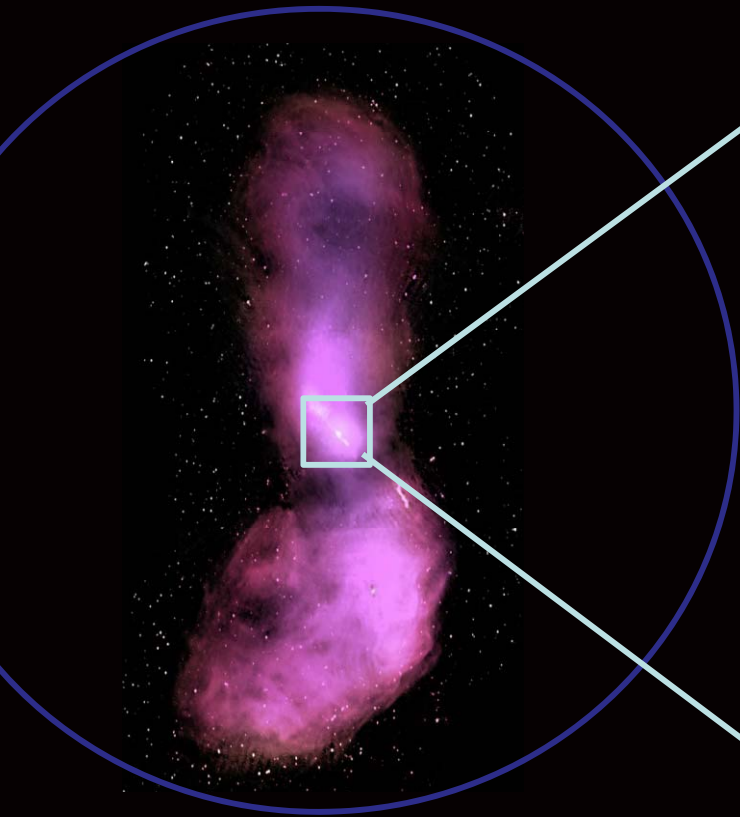
Survey speed:  
x300 faster than HESS



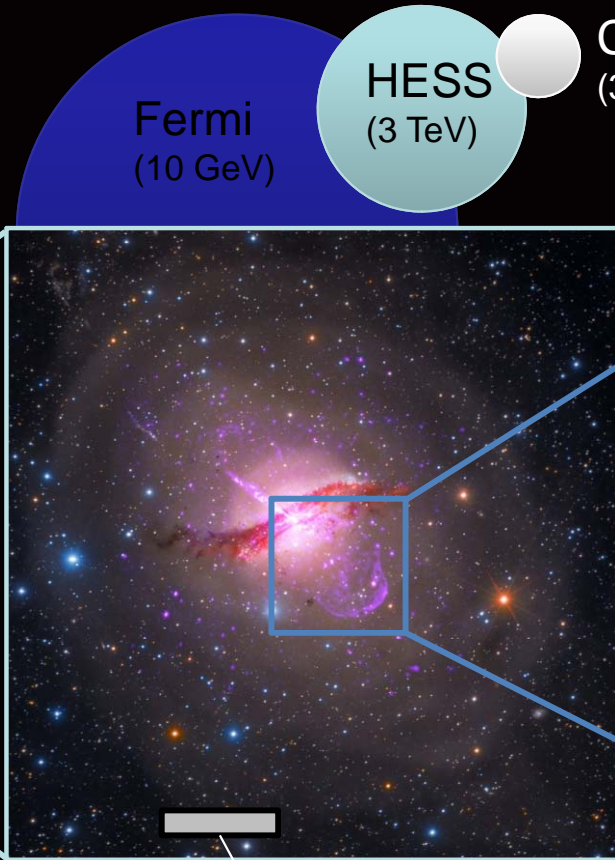


# Angular Resolution

8° CTA FoV



Example: Cen A

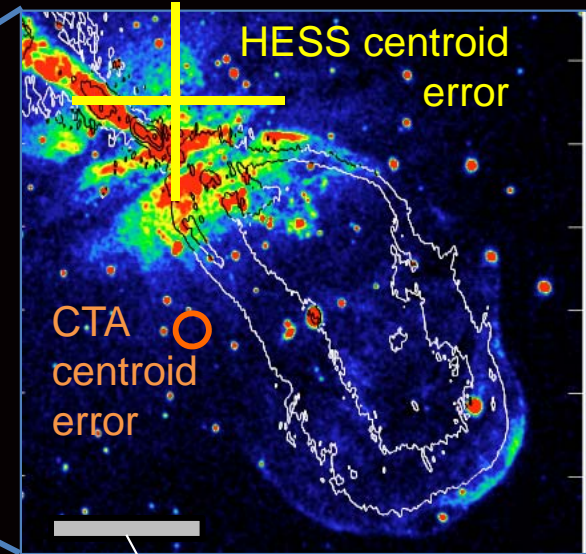


0.1°  
Typical HESS  
Resolution

CTA  
(3 TeV)

HESS  
(3 TeV)

Fermi  
(10 GeV)



2'  
CTA > 1 TeV

# CTA Implementation & Status

# CTA Consortium



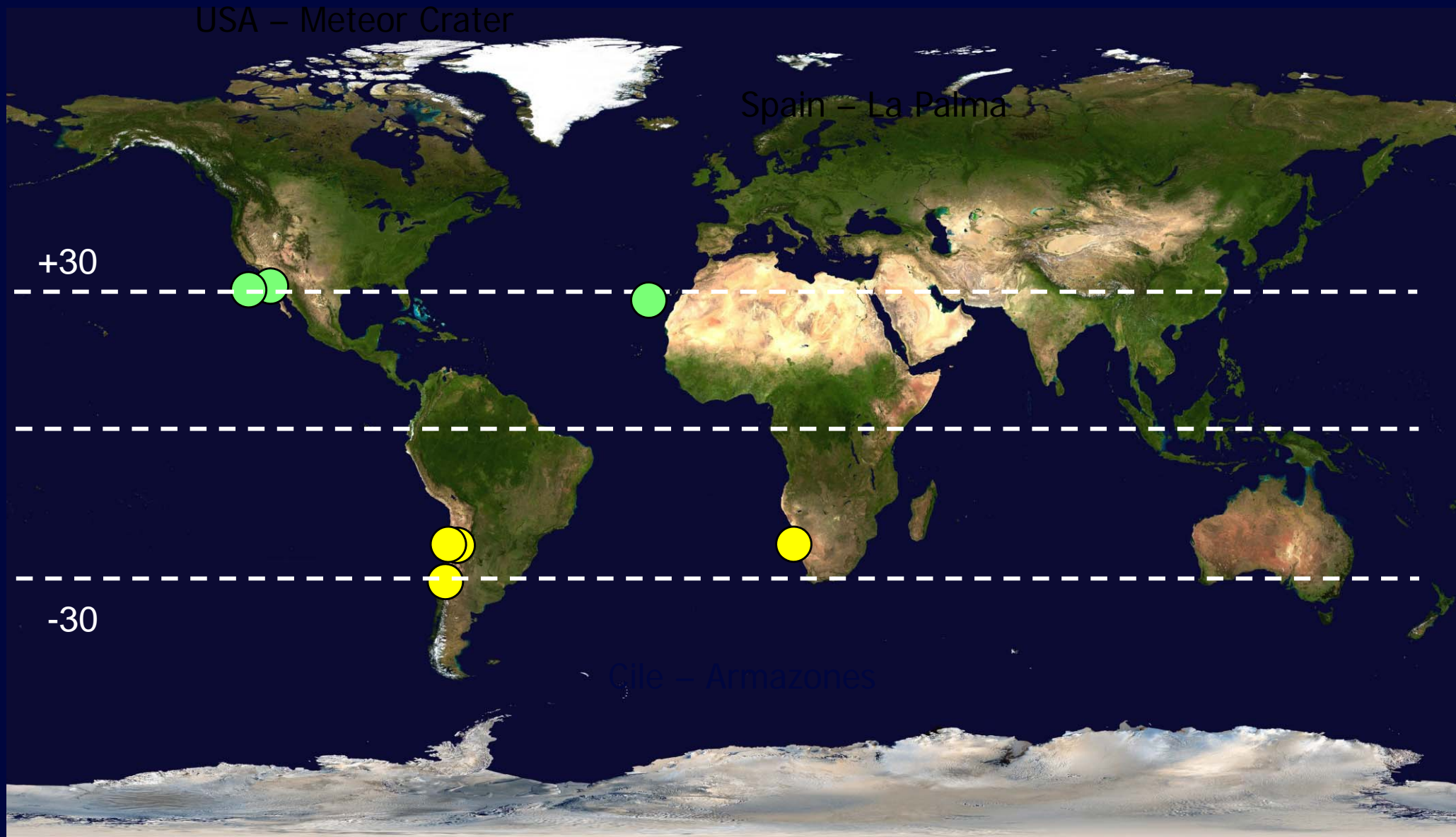
**CTA is being developed by the CTA Consortium:**



32 countries, ~1300 scientists, ~200 institutes, ~440 FTE

# Site Selection

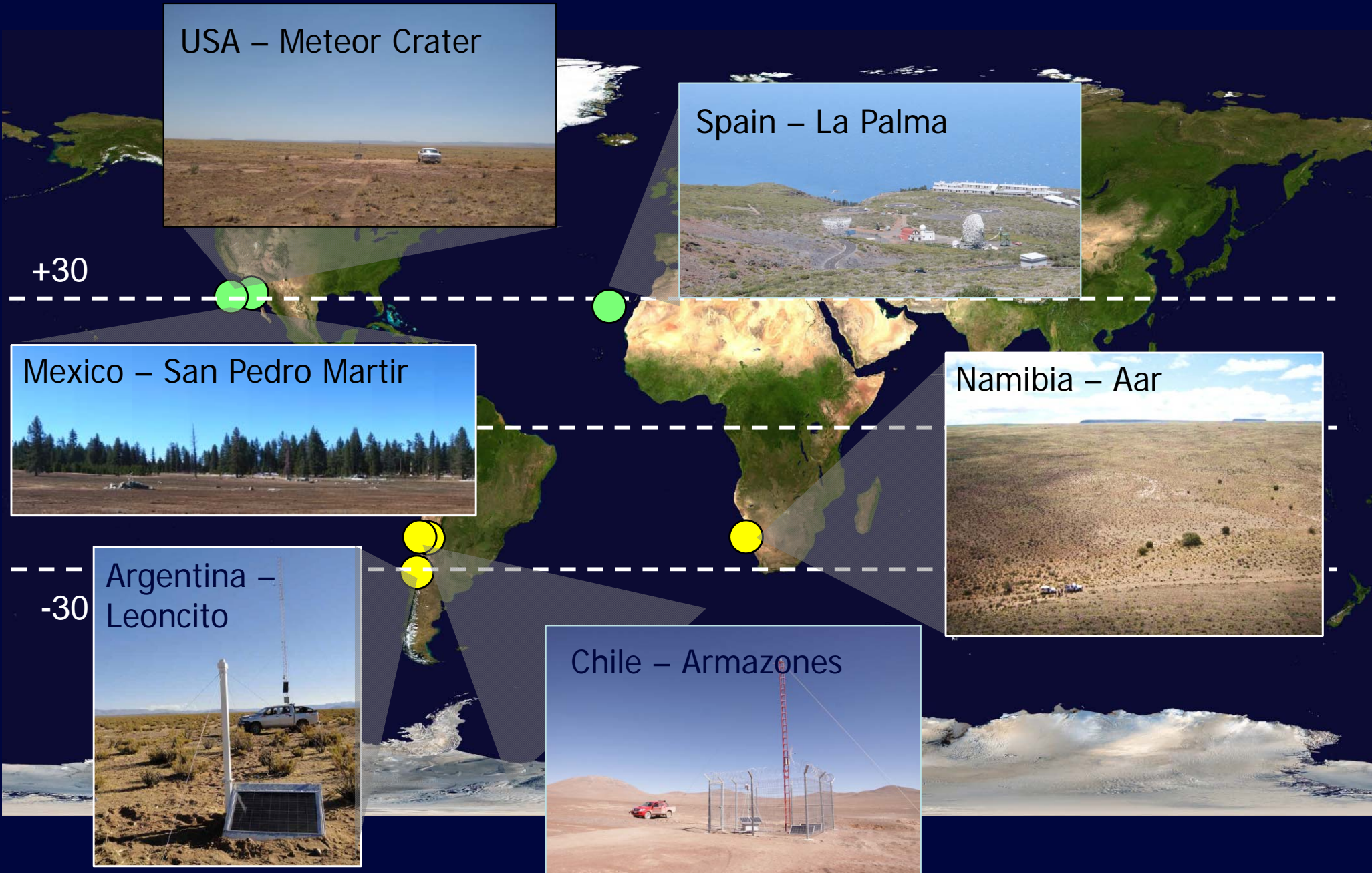
Two sites to cover full sky,  
latitude  $20^{\circ}$ - $35^{\circ}$  in N, S





# Site Selection

Two sites to cover full sky,  
latitude  $20^{\circ}$ - $35^{\circ}$  in N, S





# Prop



STATE OF ARIZONA

JANICE K. BREWER  
GOVERNOR

EXECUTIVE OFFICE

September 19, 2013

Dr. Jeff Hall, Director  
Lowell Observatory  
1400 West Mars Hill Road  
Flagstaff, Arizona 86001

Dr. Rene A. Ong, Professor  
University of California - Los Angeles  
Department of Physics and Astronomy  
Los Angeles, California 90095

Dear Drs. Hall and Ong:

As Governor of Arizona, I would like to reiterate and reinforce our state's strong and continued support of the Cherenkov Telescope Array (CTA) initiative. Arizona takes great pride in our astronomy industry – and recognizes its immense value to our ever-improving economy – we remain keenly interested in bringing this powerhouse observatory to the Grand Canyon State.



**West Site:  
Yavapai Ranch**

**East Site:  
Meteor Crater**

*Map of a portion of Arizona near Flagstaff, AZ. The access routes from the East Site (A) and the West Site (B) to Flagstaff (C) are shown in blue. The Grand Canyon starts at the top of the figure.*

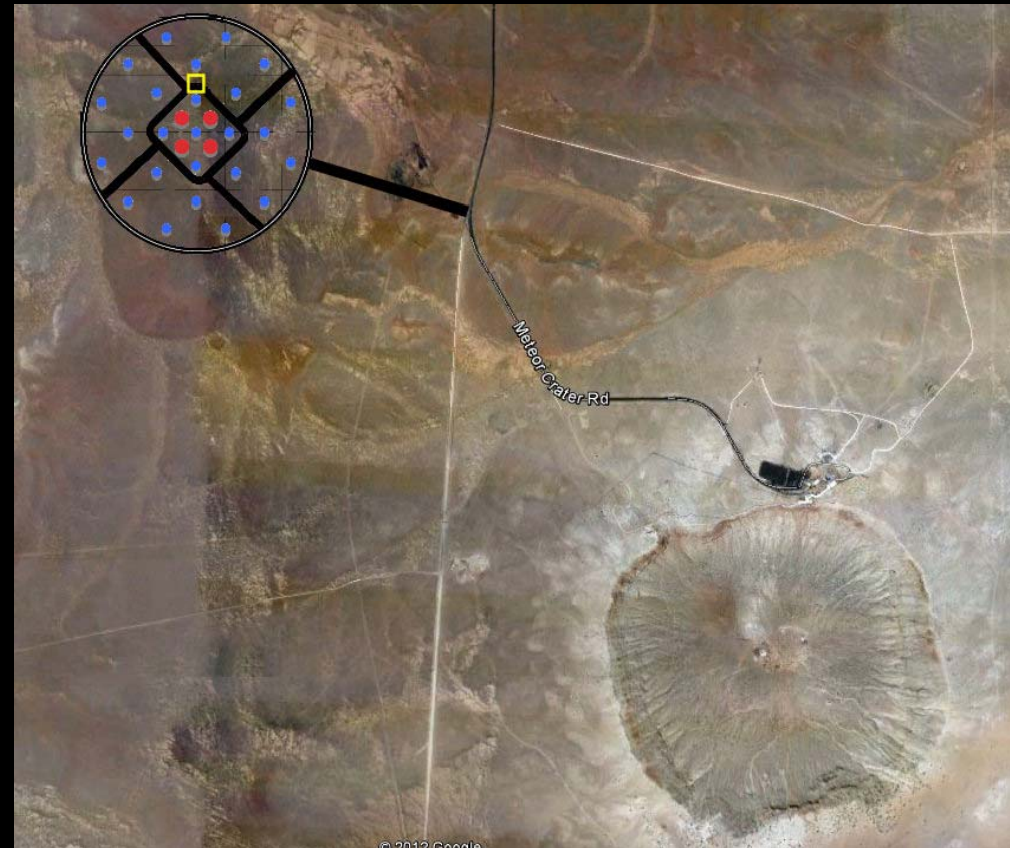


# Meteor Crater Site

CTA Reference Site superimposed on local satellite imagery to show approximate scale and road configuration.



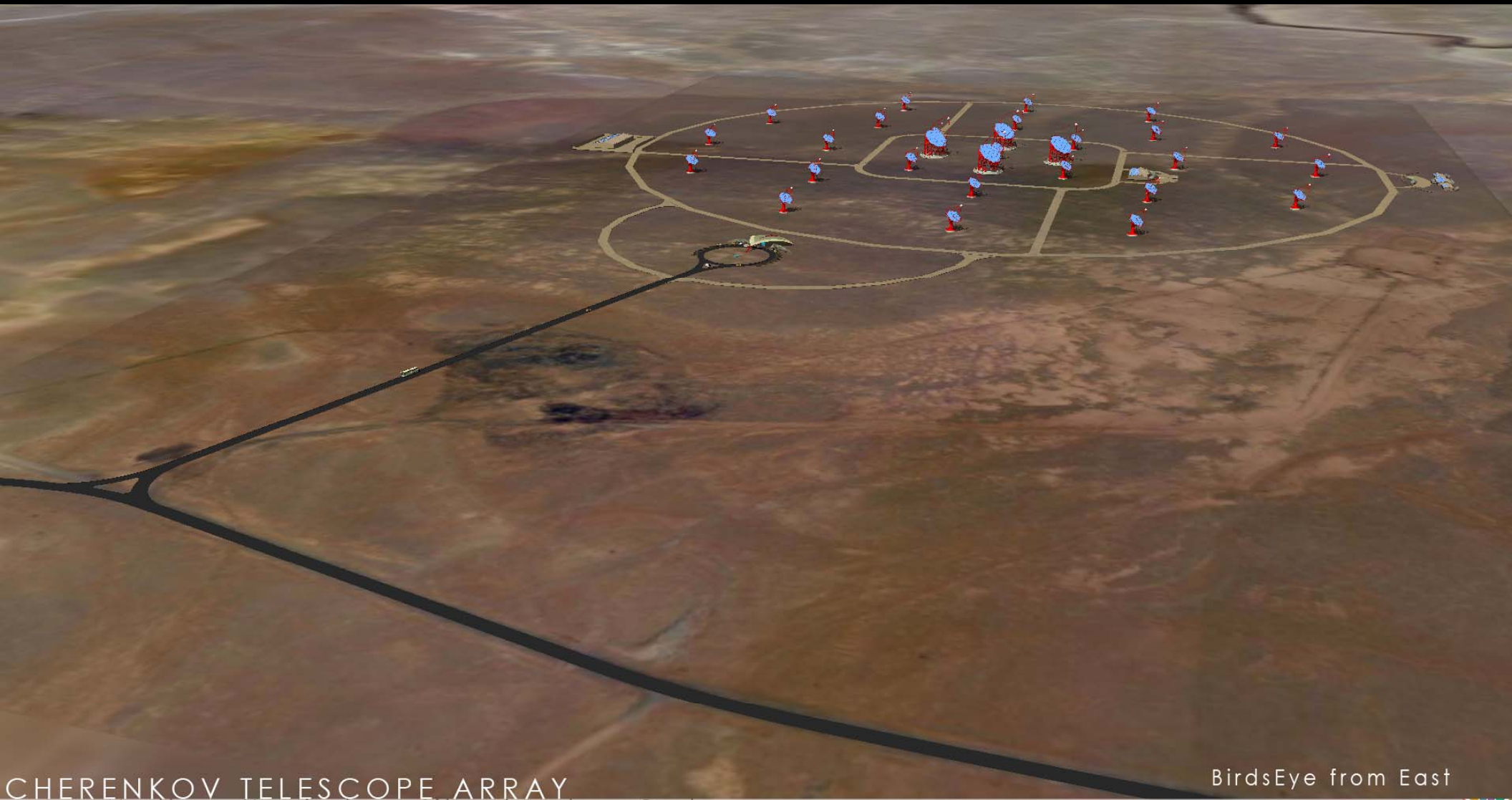
Wide view showing highway I-40 and the nearby railroad siding (9 km from site along paved road).



Zoom showing shortest route for access road (thick black line) and Atmoscope (yellow square).



# CTA at Meteor Crater Site



CHERENKOV TELESCOPE ARRAY  
Northern Hemisphere Site at Meteor Crater



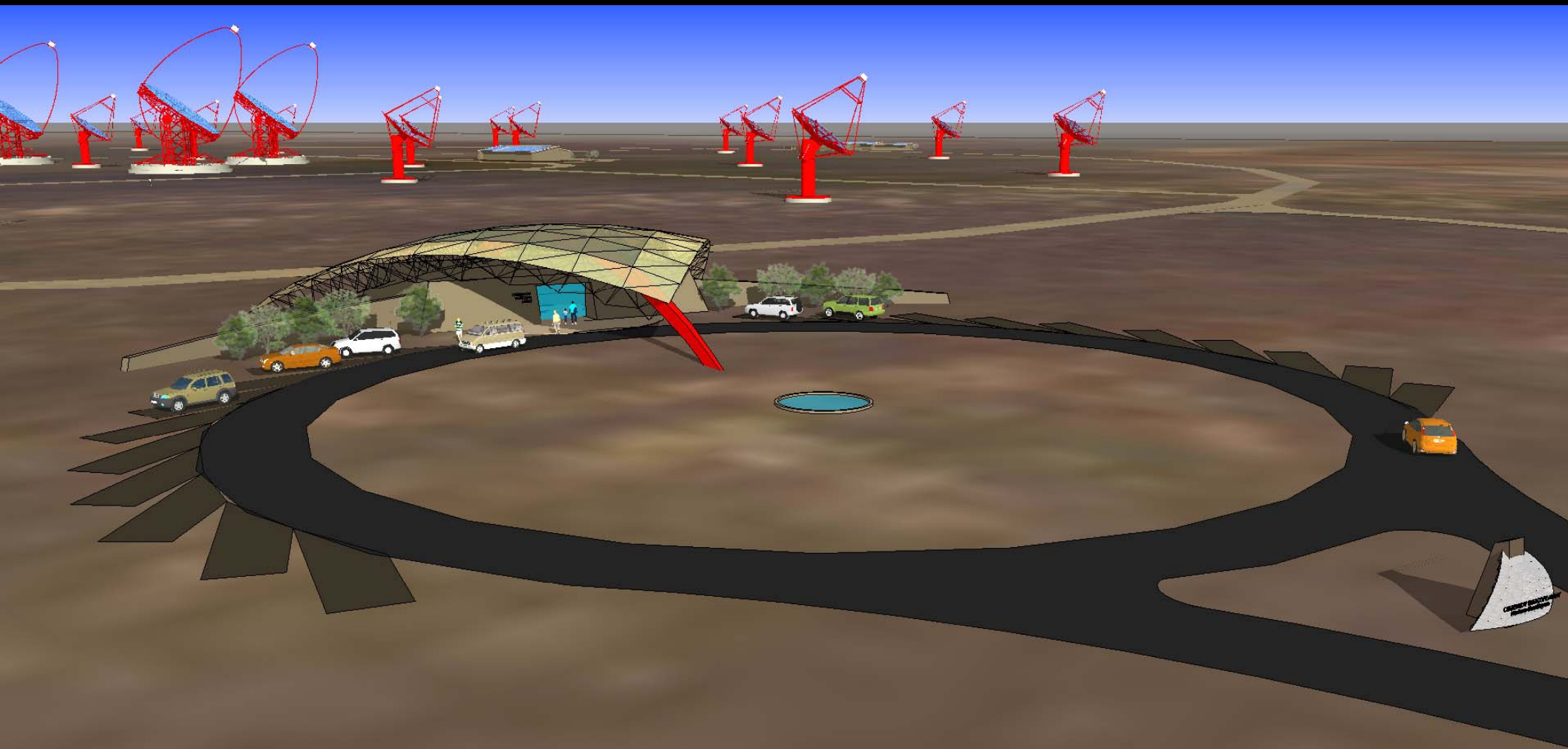
Copyright © 2012

BirdsEye from East

CATALYST ARCHITECTURE



# CTA at Meteor Crater Site



CHERENKOV TELESCOPE ARRAY  
Northern Hemisphere Site at Meteor Crater

Copyright © 2012

Visitor Center

CATALYST ARCHITECTURE





# Selected Sites for CTA



## La Palma, SPAIN



## Paranal, CHILE

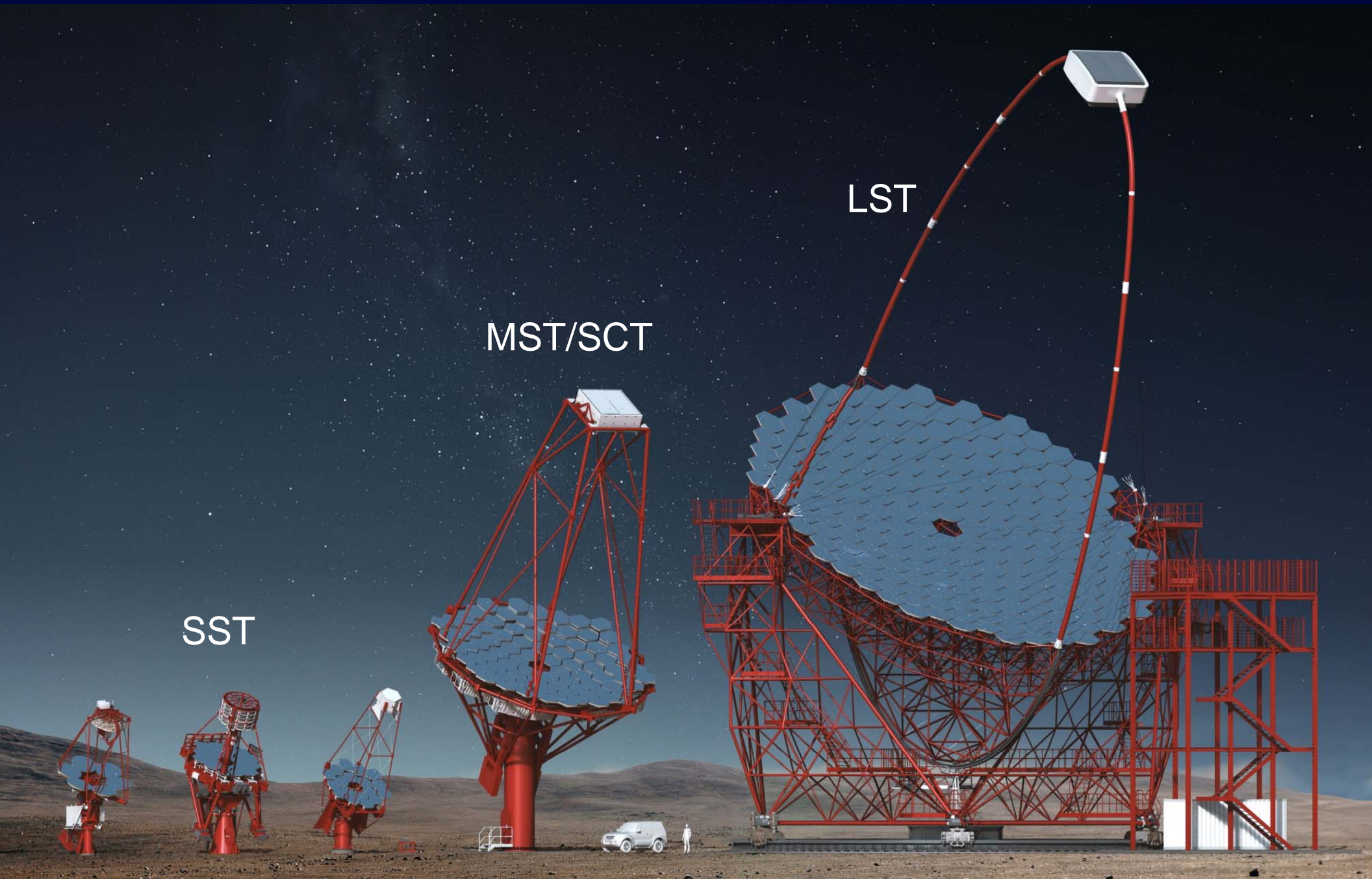


## Namibia Aar

● Under Negotiation    ● Back-up Sites



# CTA Telescope Types





# Large Telescope (LST)

23 m diameter /  $f = 28\text{m}$   
390 m<sup>2</sup> dish area  
1.5 m mirror facets

4.5° field of view  
0.1° pixels  
Camera  $\varnothing$  over 2 m

*Carbon-fiber structure  
for 20 s positioning*

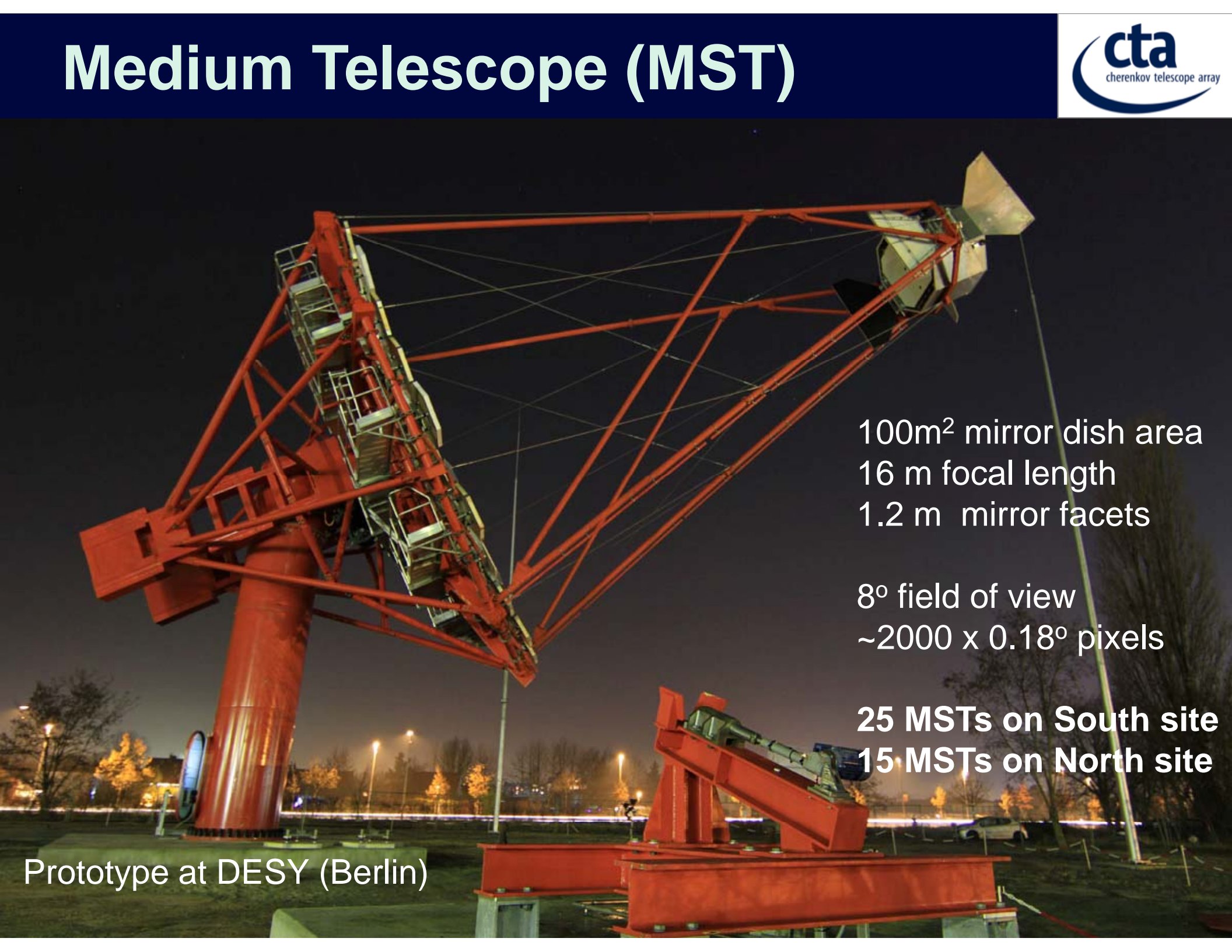
Active mirror control

**4 LSTs on South site  
4 LSTs on North site**

**First LST construction  
underway (La Palma)**



# Medium Telescope (MST)



100m<sup>2</sup> mirror dish area  
16 m focal length  
1.2 m mirror facets

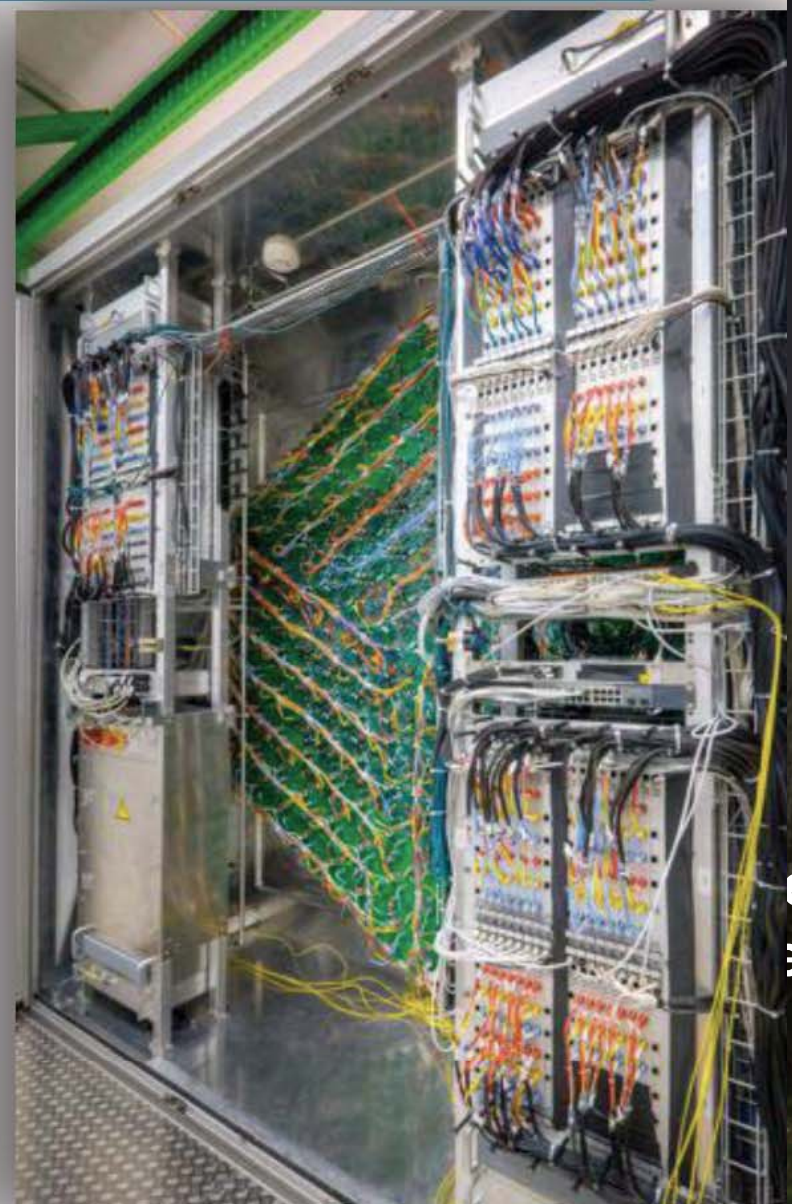
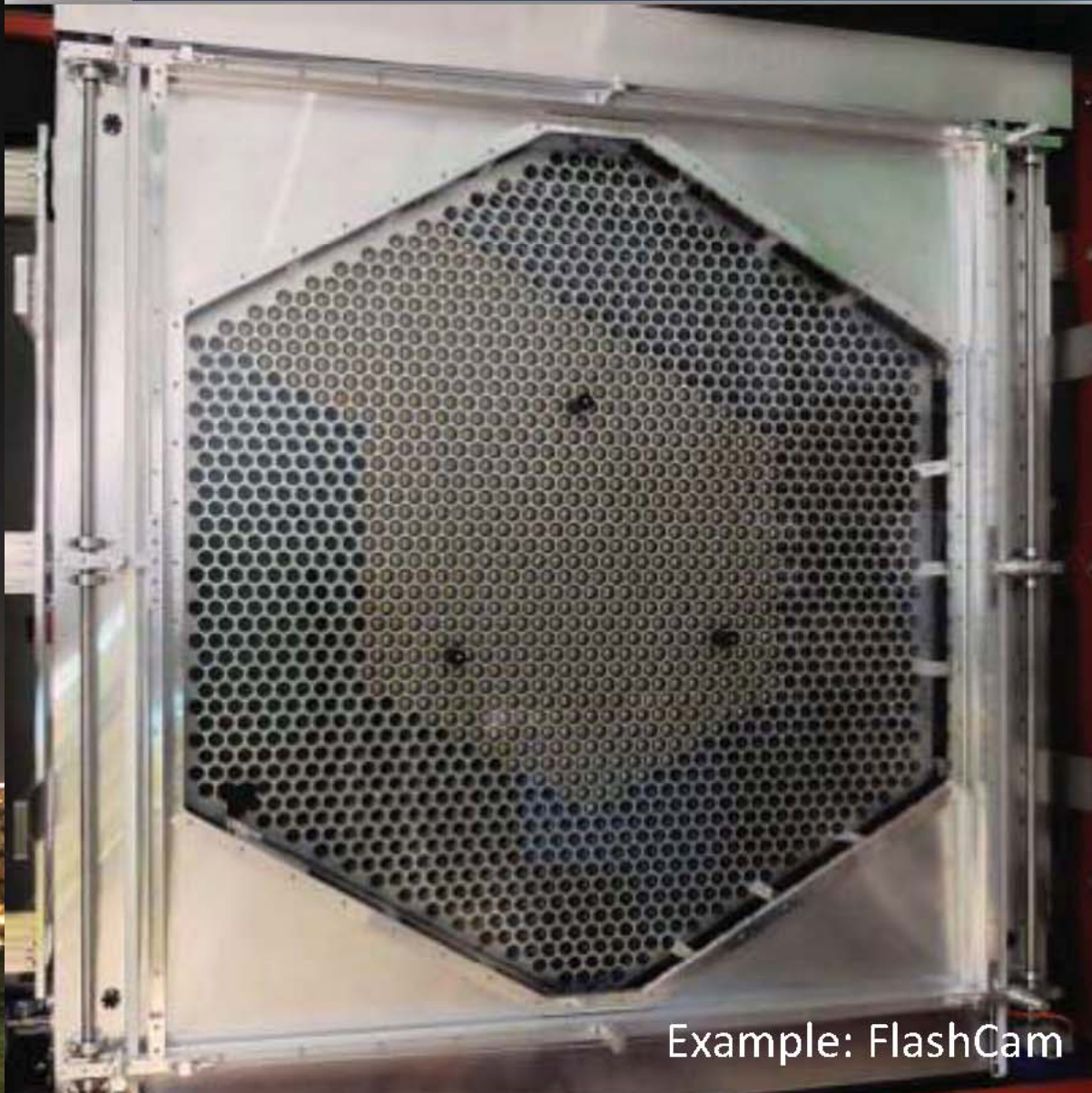
8° field of view  
~2000 x 0.18° pixels

25 MSTs on South site  
15 MSTs on North site

Prototype at DESY (Berlin)



# MST Integrated Camera

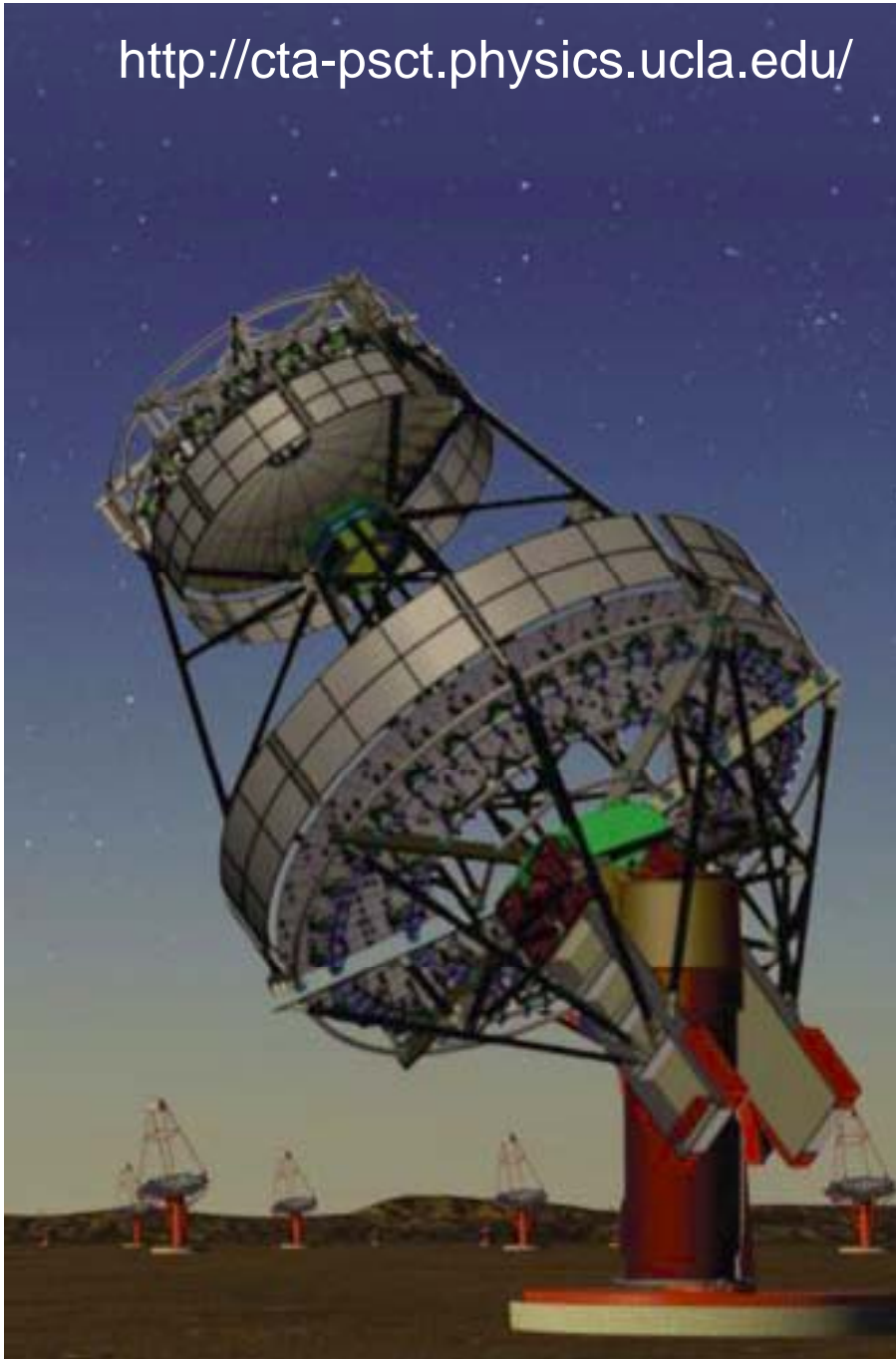




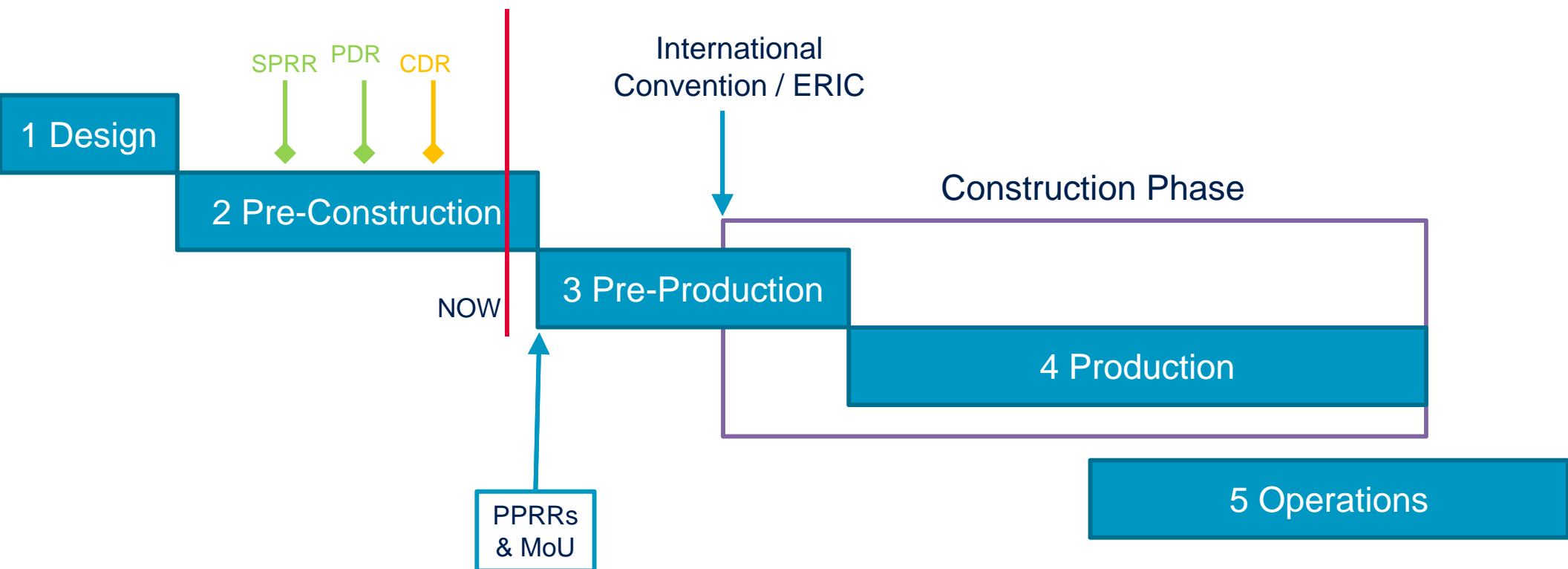
# US Contribution: Dual-Mirror MST

<http://cta-psct.physics.ucla.edu/>

- Schwarzschild-Couder design (V. Vassiliev et al.)
- 9.7m primary, 5.4m secondary
- 11328 x 0.07° Si-PMT pixels
- 8° field-of-view
- Prototype under construction: Whipple Obs. (Arizona, USA)



# CTA Phases & Timeline



- 2016-7: Hosting agreements, site preparations start
- 2018: Start of construction
- Funding level at ~65% of required for baseline implementation
  - start with *threshold implementation*
  - additional funding & telescopes needed to complete baseline CTA
- Construction period of ~6 years
- Initial science with partial arrays possible before construction end



# CONCLUSIONS



- With many discoveries, VHE  $\gamma$ -rays are now a well-recognized astrophysical discipline & part of growing multi-messenger science.
- VHE photons explore the very non-thermal universe and key questions in fundamental physics
- Outstanding science potential & power of atmospheric Cherenkov technique → CTA

- **Cherenkov Telescope Array (CTA)**

*Outstanding sensitivity & resolution over wide energy range*

*Far-reaching key science program*

*Open observatory with data released to public*

*CTA requires a broad partnership of countries and communities – including, hopefully, the US*

